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Electric Bus Power Consumption Study in Nordic Conditions

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<p>This Master's thesis was assigned by VDL Bus & Coach. The purpose was to gather and analyze energy consumption information of VDL electric city buses driving in Nordic climate conditions. The aim was to collect the data with a controlled test using a test bus and from buses delivered to the Nordic countries in 2018 and 2019.</p> <p>The research data was collected with ZF Openmatics service and analyzed in the Microsoft PowerBI application. The results were combined with literature research of the subject. Unfortunately, the practical tests planned for this thesis could not be carried out. However, on the basis of the research data acquired for this thesis it was possible to draw conclusions on energy consumption of VDL electric buses in different driving situations when they were used in cold climate conditions.</p> <p>The collected data shows that the consumption of the electrical part of the climate system was remarkably steady and is relatively lower at higher average speeds. Relative driveline consumption fluctuated significantly in different conditions and was directly proportional to long standing times with the main switch on. Braking energy regeneration was generally between 0.4 and 0.5 kWh/km.</p> <p>The results of this thesis can be used to estimate performance of similar VDL electric buses on different routes and driving cycles in cold ambient temperatures in the future.</p>	
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<p>Tämä opinnäytetyö on tehty VDL Bus & Coachille. Työn tavoite oli kerätä ja analysoida dataa VDL-sähköbussien energiankulutuksesta pohjoismaisissa sääolosuhteissa. Dataa oli tarkoitus kerätä testibussille tehtävästä käytännön testistä ja vuonna 2018 ja 2019 pohjoismaihin toimitetuista sähköbusseista.</p> <p>Data tutkimusta varten kerättiin ZF:n Openmatics-palvelulla ja analysoitiin Microsoft PowerBI -applikaatiolla. Tulokset liitettiin kirjallisuustutkimukseen aiheesta. Suunniteltuja käytännön testejä ei onnistuttu toteuttamaan.</p> <p>Tätä työtä varten kerättyyn dataan perustuva tutkimus tuotti kuitenkin tarpeeksi tulosta johdopäätösten tekemiseen VDL-sähköbussien energiankulutuksesta eri tilanteissa ajettaessa kylmissä sääolosuhteissa. Kerätyn datan perusteella lämmitysjärjestelmän sähköisen puolen energiankulutus on yllättävän vakaa eri olosuhteissa ja on suhteellisesti pienempi suuremmilla keskinopeuksilla. Voimalinjan suhteellinen kulutus vaihteli paljon eri olosuhteissa ja oli suoraan verrannollinen pitkiin seisomisaikoihin päävirrat kytkettynä. Jarrutusenergian takaisinkeräys oli yleisesti 0.4-0.5 kWh/km.</p> <p>Tämän työn tuloksia voidaan käyttää tulevaisuudessa arvioimaan samankaltaisten VDL-bussien käyttöä erilaisilla linjoilla ja ajosykleillä kylmissä sääolosuhteissa.</p>	
Avainsanat	Sähköajoneuvo, energiatehokkuus, lämmitys- ja ilmastointi, pohjoismaat

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Appendix 1. Complete results

Abbreviations

AC	Alternating current
AVG	Automated guided vehicle
BMS	Battery management system
CAN	Controller area network
CCS	Combined charging system
DC	Direct current
ETS	Enabling Transport Solutions
EV	Electric vehicle
HPHC	High power high capacity
HPMC	High power medium capacity
ICE	Internal combustion engine
PTC	Positive temperature coefficient
SOC	State of charge

1 Introduction

1.1 Background

Electric buses have become a viable alternative to conventional diesel-powered buses in city traffic. They benefit from lower emissions, especially local emissions, as well as a higher passenger comfort due to reduced noise and vibrations. In general city buses are an easy type of vehicle to electrify since the routes they drive are almost always predetermined. However, drive range and power consumption will remain an important topic since the cost of batteries is still a large portion of the cost of an electric bus. This is especially true in the Nordic conditions, where cold climate influences the drive range negatively.

1.2 Purpose

The purpose of this Master's thesis was to gather energy consumption information of VDL electric city buses with a controlled test on a test bus and data acquired from buses delivered to the Nordic countries during the winter between 2018 and 2019 using the connectivity tool OPENMATICS. This data were combined with literature research to make product improvement suggestions based on the research. The data of actual energy consumption gathered for this thesis may be used for route planning advice for a customer in the future.

1.3 Scope of the Thesis

The scope of this thesis was limited to power consumption topics in the Nordic climate, specifically cold weather. The effects of other variables such as the number of stops, driver behavior and aggressivity of driving were only considered in combination with cold weather and how the effect of changes in these differs from the central European conditions. The product improvements that are suggested are limited to purely technical topics and do not include operational aspects such as driver instructions or route optimization.

Research questions of this thesis are as follows:

1. How much are the current vehicle models consuming during the coldest days of the winter?
2. What reasons are affecting the consumption during cold ambient temperatures and how much?

1.4 Limitations

The original plan for this thesis was to make actual field tests to a bus. This proved to be impossible due to several logistic issues and the unusually warm weather of the winter between 2018 and 2019 at the test location as well as other possible Nordic locations. Therefore, the actual study for this thesis was limited to the data collected with the ZF OPENMATICS service.

Collecting the data was difficult since they were normally only available for a month from the day the buses were driven. Luckily it was possible in the end to collect the needed consumption data during the complete implementation period, but unfortunately ambient temperature data were corrupted and could not be used. For this purpose, weather history data was collected from timeanddate.com and by using it, it was possible to sort vehicle data from the coldest days and base this study on them.

Intermittent driving during the implementation limited the amount of data collected from OPENMATICS, since not all the buses were constantly used during the coldest days. Luckily there was just enough driving to be able to proceed with the study and draw conclusions.

The overall lack of exceptional cold days was a big limitation to the overall purpose of this thesis. Temperatures at any location were not below -20°C and data on driving in truly arctic climate could not be gathered.

1.5 Previous Work

The winter between 2018-2019 was the first winter during which the production version VDL electric buses were delivered to the Nordic countries, so not much previous work had been carried out regarding the topic of this thesis. There had been previous prototype versions, but their systems were very different from the production versions included in this study. Therefore, they could not be compared.

There had been a winter test during the previous winter in Sweden by VDL ETS. The original plan of practical field testing would have been to continue that test. Also the research plan made for this thesis had its ideas from that test. However, since the test carried out by VDL ETS was confidential and the practical part of this thesis could not be arranged, this previous work is not explained in this thesis either within the VDL companies or outside them.

2 General Theory

2.1 Lithium-ion Batteries

2.1.1 Principles of Lithium-ion Batteries

The first lithium-ion batteries were introduced by Sony in 1990. The applications were at first handheld devices such as mobile phones and laptops but were later made to fit larger applications such as vehicles and energy storage systems. The production of the lithium-ion battery for vehicles is a relatively new technology, penetrating the market around the year 2010 [12].

A lithium-ion battery consists of a negative electrode and a positive electrode, a separator, an electrolyte and two current conducting terminals. While discharging, the electrolyte carries positively charged lithium-ions through the separator from the negative to the positive electrode. This process is reversible. In other words when the battery is being recharged, the lithium-ions move from the positive to the negative electrode. By convention the negative electrode is called anode and the positive electrode cathode, describing the situation while the battery is being discharged. The separator is a semi-permeable membrane and acts as an insulator for individual electrons but lets the charge carrying lithium-ions through at the same time ensuring that the electrodes do not short circuit.

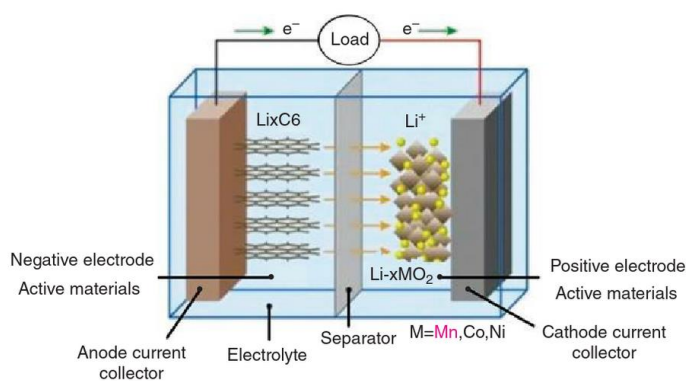


Figure 1. Basic structure and operation of a lithium-ion battery [13, page 10]

Positive electrode materials are intercalation compounds of lithium-ion, for example LiNiO_2 , LiMn_2O_4 , LiCoO_2 . The negative electrode material is typically graphite Li_xC_6 , but can also be TiS_2 or V_2O_5 . The electrolyte is a solvent such as ethylene carbonate,

propylene carbonate or dimethyl carbonate in which lithium salts are soluble. Typical separator materials include polyethylene or polypropylene [13, page 9].

The specified voltage range of an individual lithium-ion cell is commonly from 3 volts to 4.2 volts. In a vehicle application, several cells are typically connected as a pack, and several packs are then connected as a complete battery system in the vehicle. This can be done in several different series-parallel configurations to achieve the system design voltage and capacity.

The advantages of lithium-ion batteries over lead-acid batteries used in ICE vehicles include high energy density, slow self-discharge, and the lack of a memory effect. Modern lithium-ion batteries also have a relatively high cycle life [12, page 4].

The disadvantage of lithium-ion batteries is that they have relatively narrow operating conditions regarding temperature, current and cell voltage. The use of the battery outside these conditions can compromise cell integrity or user safety. For example, discharging the battery below the manufacturers lower voltage limits can cause degradation of the electrodes and by doing so repeatedly can result in cell failure and thermal runaway. Respectively, charging the battery over the highest specified voltage has a risk of rapid exothermic degradation of the electrodes and a thermal runaway as well. [13, page 5-6]

Thermal runaway in the context of lithium-ion batteries means rapid self-heating of the battery due to the chemical potential energy of its electrodes being released uncontrollably. Thermal runaway can happen with almost any battery chemistry, but in lithium-ion batteries it is more dangerous due to a few reasons. Firstly, lithium-ion batteries have a relatively high energy density, so also relatively high amounts of energy may be released by them in case of a thermal runaway. Secondly, the hydrocarbon-based electrolyte of lithium-ion batteries is flammable, in worst case acting as combustion material. In order to a thermal runaway to begin, heat generation inside the battery needs to exceed heat loss. Self-heating of graphitic anodes in the electrolyte begins at 70-90°C, after which it might take two days to reach thermal runaway. If the initial temperature is higher, thermal runaway will happen earlier since it starts almost immediately above 150°C, when the separator melts and permits short circuit of the electrodes. [13, page 46-47]

Due to the limits explained above and several other safety and reliability related reasons, lithium-ion batteries require complex electronic protection system, commonly called a

battery management system. At its simplest the battery management system protects the battery against overcurrent while discharging or charging, over- or undervoltage, too high temperatures, charging at too low temperatures and cell imbalance. [13, page 22,23].

The BMS functions explained before are typically performed by single circuit boards for each cell or pack of parallel connected cells. Larger battery systems, for example battery systems used in an EV, usually have a master BMS that is communicating with the individual circuit boards monitoring each cell or a smaller pack of cells.

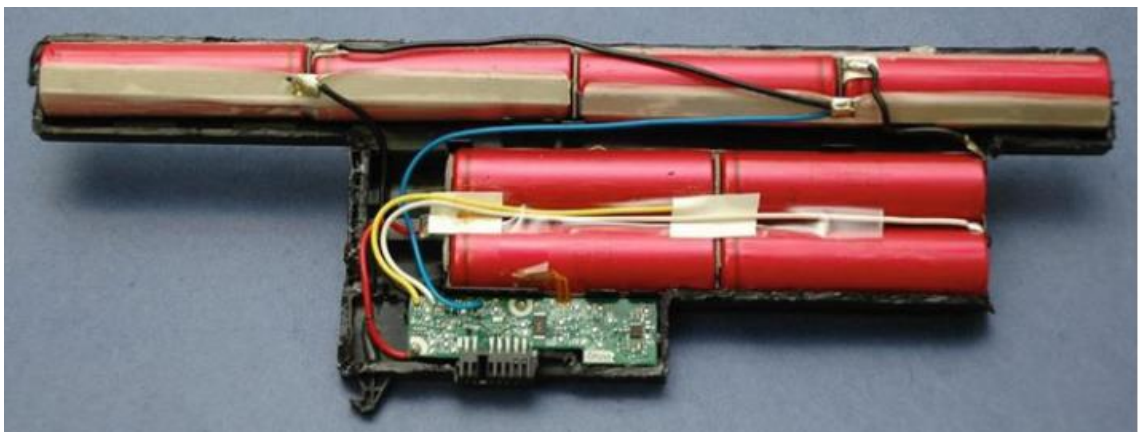
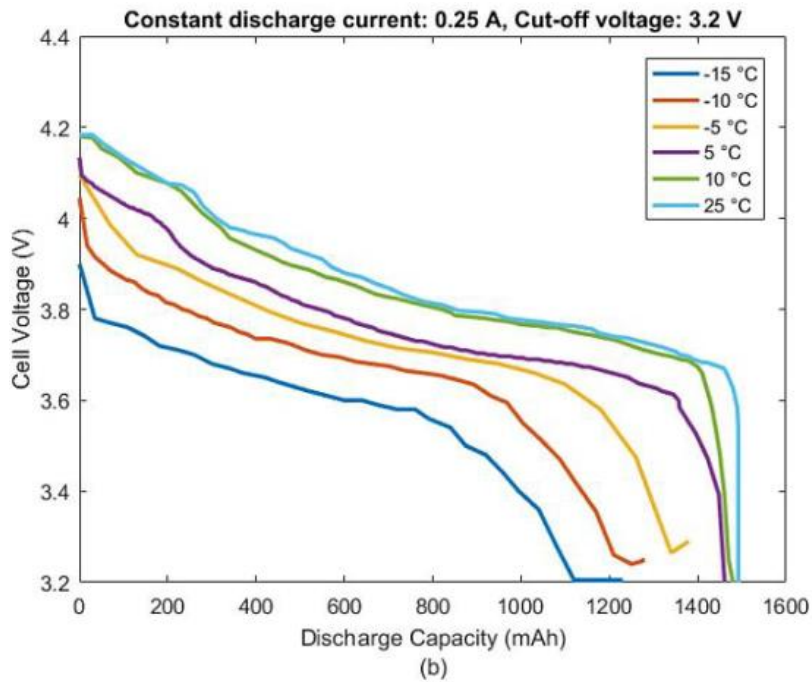


Image 1. A protection circuit board inside a lithium-ion battery pack [13, page 6]

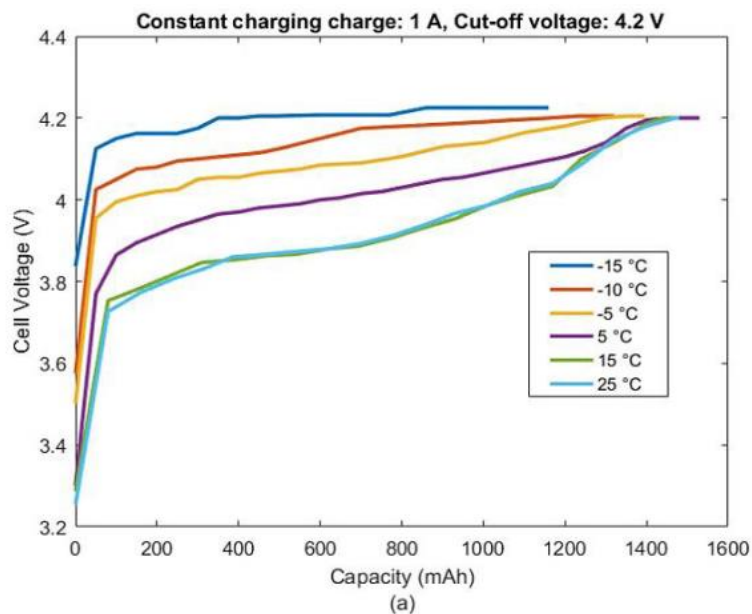
2.1.2 Issues in Low Temperatures

While lithium-ion batteries are the choice of today in electric vehicles, they have issues when used in cold temperature. The discharge capacity of a lithium ion battery starts to drop significantly in sub-zero temperatures as can be seen in graph 1 [1]. The cut-off voltage defined in a typical battery management system is reached sooner since the voltage drops earlier.



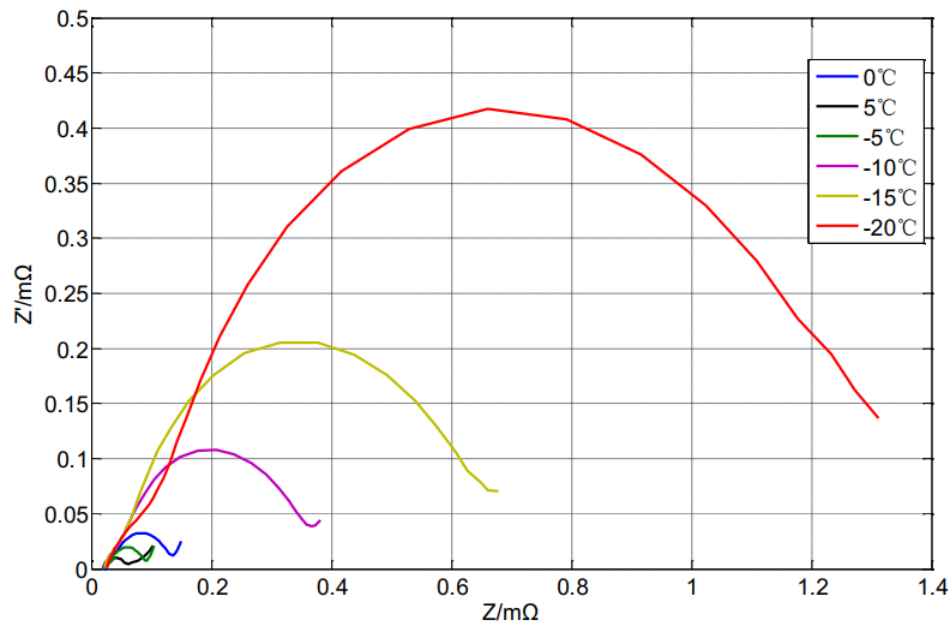
Graph 1. Cell voltage drop while discharging in several temperatures.

The same effect occurs when charging the battery but is even stronger. At -15, the available SOC can be only 77% of the SOC at optimum temperature and cell voltage rises very quickly close to cut-off voltage, reducing the maximum charging rate available.



Graph 2. Cell voltage rise while charging in different temperatures.

The effects shown above occur mainly due to higher internal resistance causing a heating effect inside the battery. The rise of internal resistance in a lithium-ion battery is demonstrated by Shanshan Guo, Yun Liu, and Lin Li [2] in an impedance spectroscopy measurement. The results can be seen in graph 3 in the form of a Nyquist plot. This shows how a lithium-ion battery impedance rises below -5°C temperatures [2].



Graph 3. Impedance spectroscopy measurement of a lithium ion battery in several temperatures.

The higher internal resistance will heat the battery. However, once warmed up the resistance will be lower. While reaching cut-off voltage quicker is a momentary problem when the battery is cold, there are also more permanent effects to using lithium-ion batteries in low temperatures, especially when charging them. Normally during the charging process lithium moving from the cathode to the anode should intercalate in the graphite anode:



However low temperatures promote lithium plating formation while charging, where all of the lithium will not intercalate with the graphite anode and metal lithium starts to accumulate on the anode surface:



When metal lithium starts forming on the anode, vacancy sites for lithium intercalation decrease. This further promotes lithium metal plating as more and more lithium-ion current towards the anode contribute to plating and less to intercalation as seen in Figure 2.

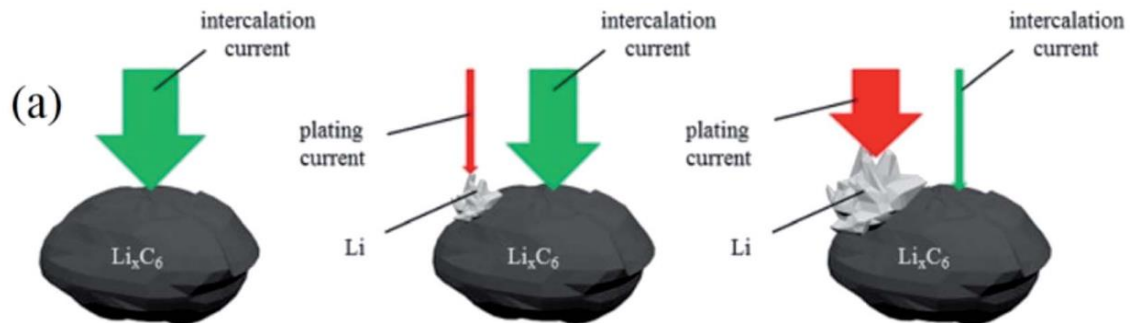


Figure 2. Plating current on the anode [3].

After metal lithium has formed on the anode, it is still possible for it to re-intercalate with the graphite due to a potential difference between the metal lithium and the Li_xC_6 . The metal lithium might also react with the electrolyte to form a film on the surface of the anode, permanently decreasing capacity. The deposited lithium metal also poses a safety risk. It often builds in the form of needles or dendrites that might penetrate the separator and cause a short circuit. There is also a risk of thermal runaway due to intense exothermic reaction of the deposited lithium and the electrolyte [3].

Due to issues discussed in this chapter it can be concluded that lithium ion batteries in general should be warmed up before used, especially when charging them. In the case of the electric bus that will cause a longer charging time when first started on a cold morning.

2.2 Dynamics

While the nature of this thesis does not make possible the optimization of driving dynamic related topics of the tested bus model in the Nordic climates, it is important to understand the effects of cold temperature on these items as well to get a complete picture of power consumption in a bus driving in the cold Nordic climates. It can be easily thought that increase in energy consumption is completely caused by heating components and interior of a city bus but this is not entirely true.

This chapter will introduce the theory of drag resistance and roll resistance which have the largest impact on energy consumption of a moving vehicle driving dynamics wise. Also the effect of snowy roads and cold temperatures on these two factors will be explained.

2.2.1 Effects of Aerodynamic Resistance

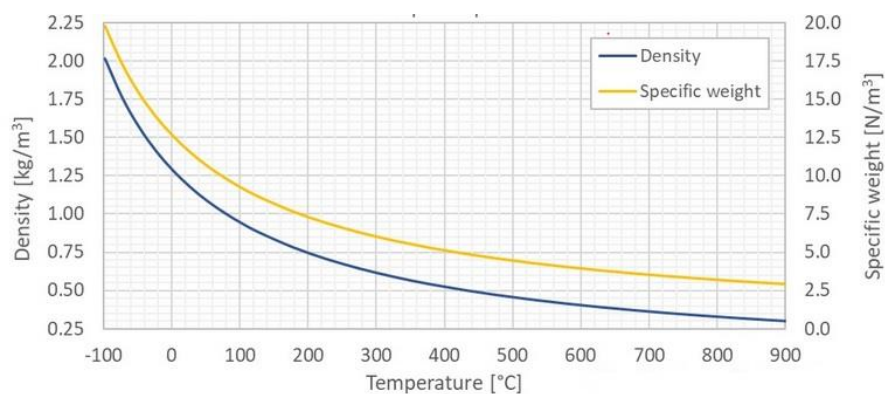
The aerodynamic resistance for a vehicle comprises of air flowing over the exterior of the vehicle as well as air flowing through the radiator. The later typically accounts less than 10% of the total air flow and since in an electric bus the radiator configuration plays even a smaller role in the total aerodynamic resistance due to its position in and especially in wintertime when it is rarely used, this section will only consider external aerodynamic resistance.

The drag force experienced by a vehicle due to air resistance can be calculated with the following formula:

$$R_a = \frac{\rho}{2} C_D A_f V_r^2 \quad (3)$$

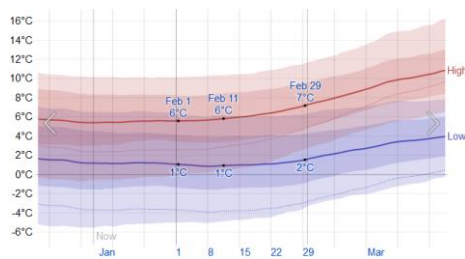
Where R_a is the drag resistance, ρ is the mass density of the air, C_D is the aerodynamic factor determined by several factors such as the form of the vehicle, and A is the frontal area of the vehicle. [4, page 210]

For the topic of this thesis factors C_D and A are not interesting, since they remain the same when driving conditions change. What is interesting in this case is the extra drag caused by changes in air temperature affecting mass density of the air as can be seen in the graph below:

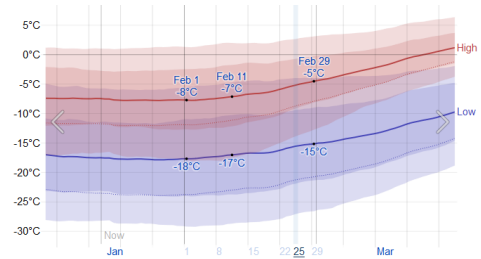


Graph 4. Air density and specific weight at atmospheric pressure [20]

As temperature drops, air density will increase increasing the total drag resistance. For a comparison, the average low temperature in February in Amsterdam where the largest fleet of VDL electric buses were driving at the time when this thesis was being written is +1C (graph 5a) while average low temperature at the VDL winter test location in Jokkmokk is -17C (graph 5b). Air at an +1C temperature weighs 1,287 kg while air at -17c weighs 1,377 kg both measured at atmospheric pressure.



Graph 5a. February average weather in Amsterdam [21]



Graph 5b. February average weather in Jokkmokk [21]

Using these values one can calculate the increase of drag due to temperature difference:

$$1,377 \text{ kg} / 1,287 \text{ kg} = 1,07 \quad (4)$$

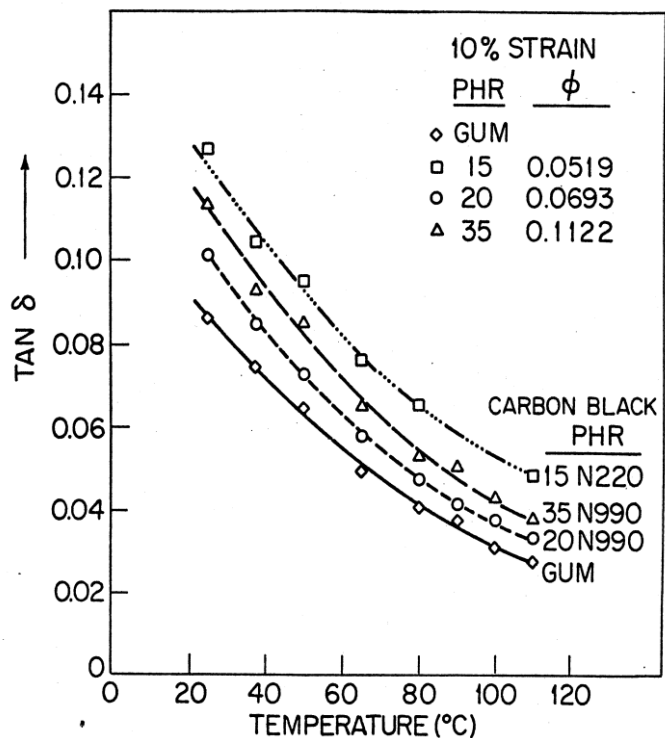
It can be concluded that in average low temperatures at the test location in February the vehicle would experience a drag force that is approximately 7% higher than in Amsterdam.

2.2.2 Rolling Resistance

Three general factors contribute to rolling losses of a pneumatic tyre such as a bus tyre:

- Friction losses or slip between the tyre and the road
- Windage losses due to air resistance to the rolling movement of the tyre
- Hysteretic losses of the tyre material as the tyre deforms and returns back to its normal shape

In normal driving conditions on dry asphalt the first two are negligible and rolling losses are almost entirely due to hysteretic losses. Cold temperature has a direct effect on hysteretic losses of tyres as can be seen in graph 5. Generally rubber compounds used in tyres have a much higher hysteretic loss at ambient conditions when first started driving and will drop significantly when equilibrium running temperature is reached. Further, higher tyre temperature will cause higher tyre inflation which will reduce losses even more. [5, page 3]



Graph 6. Influence of temperature on loss characteristics of a typical rubber compound [5, page 5]

In practice a more significant cause for larger rolling resistances during winter period is not directly caused by colder temperatures, but by uneven road conditions due to snow and ice in wintertime. This will cause friction losses as the wheel starts to slip in low friction, and the unevenness will make the tyre deform more than in smooth rolling, increasing hysteretic losses.

Road conditions have an effect on rolling resistance especially in urban stop and go type driving, typical of a city bus. Haakana et al. [6] demonstrated with a practical test that in an urban driving cycle the rolling resistance can be 20% larger with snow on the road,

compared to smooth asphalt. This can be seen in table 1. The test was carried out with a passenger car size EV.

road surface ambient temperature	asphalt -20 °C	old snow -20 °C	new snow -20 °C
cycle	kWh/km	kWh/km	kWh/km
NEDC	0.192	0.196	0.201
Helsinki City	0.173	0.211	0.208
Road, FIN	0.251	0.267	0.267

cycle	ratio	ratio	ratio
NEDC	100 %	+2 %	+5 %
Helsinki City	100 %	+22 %	+20 %
Road, FIN	100 %	+6 %	+7 %

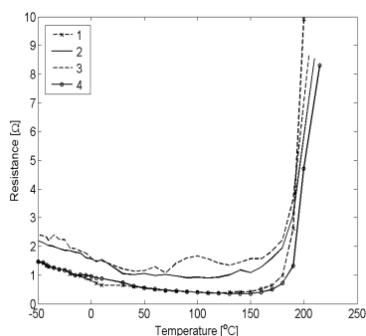
Table 1. Measured energy uptake from the grid for each cycle and temperature [6, page 27]

2.3 Auxiliary Heating for an Electric City Bus

2.3.1 PTC Resistor Heating

With the increase of efficiency in combustion engines, less heat is transferred to the coolant and is available for heating purposes during winter time. Especially newer diesel-powered passenger cars have had decreased comfort level due to slower heating times. For this problem, PTC resistor heating is becoming more and more popular solution [11, page 2]. With electric vehicles, there is only a fraction of excess heat available from the powertrain for heating that even a modern combustion engine would produce, making an extra heater a necessity rather than a comfort accessory. While there are more efficient solutions for electric extra heating, mainly a heat pump, the PTC resistor is a reliable auxiliary heater for a vehicle with steady efficiency in any ambient condition.

A PTC heater is simply an electric resistor which has a rising resistance curve with respect to its temperature, as can be seen in graph 6.



Graph 7. Temperature-resistance characteristics of a typical PTC heater [11, page 5]

Typical PTC resistor materials include high density polyethylene, polymeric and titanate ceramic materials. Barium titanate ceramic materials are mostly used for PTC heaters in the automotive industry [11, page 2]

2.3.2 Heat Pumps

When an electric bus should be heated using energy from its drive batteries, energy efficiency of the heating system is extremely important as it is by far the biggest consumer of drive battery energy after the driveline itself. An obvious solution for reducing heating consumption compared to a resistor type heater is a heat pump system, in principle a similar system like used in many buildings today. A resistor type heater cannot exceed 100% efficiency, but a heat pump system is able to do that since it is able to extract energy from ambient air.

A heat pump, as well as a refrigerator or a heat engine, is a heat machine. Its operation is based on thermodynamic processes and energy flow that is opposite to a heat engine, for example a diesel engine. The idea of a heat pump is to lift a quantity of heat from a lower temperature heat source to a higher temperature heat sink. The second law of thermodynamics [22] rules that this transfer of heat must be done by the work supplied to the machine as shown in figure 3.

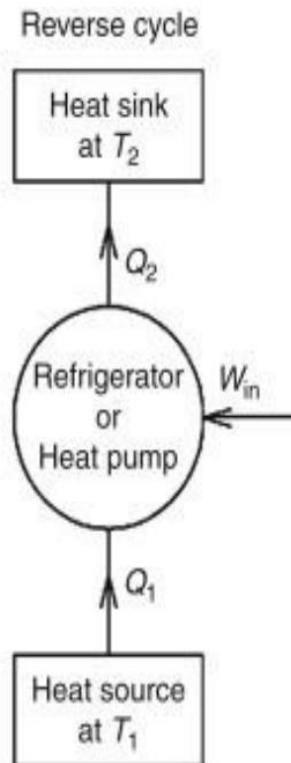


Figure 3. A reverse thermodynamic machine [7, page 2]

The quantity of heat Q_2 supplied to the sink, for example inside a vehicle, is then the sum of heat Q_1 transferred from the heat source at temperature T_1 and the work W supplied to the machine.

Theoretical maximum efficiency factor of the heat pump, called *coefficient of performance*, depends on two factors: absolute temperature of the heat source T_0 and temperature difference between the heat source T_0 and the heat sink T_1 , and can be written in the following form:

$$\text{COP} = \frac{Q_2}{W} = \frac{T_0}{(T_1 - T_0)} \quad (5)$$

Since temperatures are calculated in kelvins, in theory temperature difference between the sink and source is the largest single factor affecting efficiency.

A typical heat pump that can be used in vehicles such as an electric bus utilizes a simple vapour compression cycle to achieve the thermodynamic process explained before. Refrigerant used in the system condenses and boils at a temperature that depends on its pressure. When boiling, the refrigerant draws heat from its surroundings and when condensing, it releases this latent heat. Such device in its simplest form is shown in figure 4a. A compressor that is run by external energy compresses gaseous refrigerant to a high temperature, high pressure state. The compressed refrigerant then travels to the condenser coil where it condenses into a liquid state under high pressure and releases heat to the coil. The high-pressure liquid then travels to the expansion valve which, together with the compressor, separates the system into a high- and low-pressure zone. The refrigerant exists the expansion valve as low-pressure mist and starts to evaporate. At the evaporator coil, the evaporating refrigerant absorbs heat from the coil and travels back to the compressor where the cycle starts again. By using fans to blow or suck air through the coils, the energy can be absorbed or released to this air. Such system can be used to heat a bus for example, by mounting the evaporator coil somewhere in the exterior of the bus and the condenser coil in the internal air distribution channel. Typically, several coils are used both at the condenser and the evaporator side.

Figure 4b shows a temperature-entropy diagram of a vapour compression cycle. The area inside the rectangle with arrows indicates the work needed to lift a quantity of heat from the source to the sink, with the area in the rectangle below is indicating the transferred heat. If the temperature difference of the source and the sink gets larger, so does the required pressure difference between the high- and low-pressure zone of the system. This requires the expansion valve to restrict flow of the refrigerant more and more work is required from the compressor to pump lower density, refrigerant to higher pressure and density. The mass flow rate of the system will be lower and compressor discharge temperature higher, reducing efficiency of the system. [9, page 2]

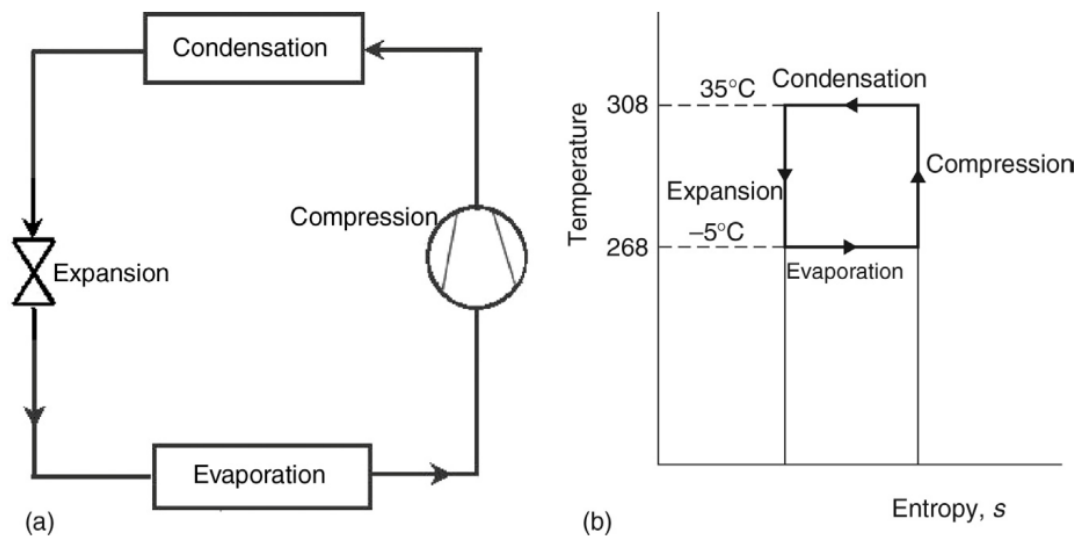


Figure 4. Vapour compression cycle heat pump system in theory [8, page 20]

There are also practical limitations concerning energy efficiency of heat pumps in vehicles used in cold climate. When ambient temperatures are around zero and relative humidity of air is high the evaporator coil will accumulate frost that acts as an insulator, preventing proper heat transfer from air to the evaporator coil. This requires some form of defrosting function in the system. The design of the coil is a very important regarding defrosting. During defrosting, the melted water should drain easily from the evaporator coil so that the coil does not freeze again when the defrost cycle ends, which will dramatically reduce efficiency. However, a microchannel heat exchanger type coil typically used in vehicle air conditioning systems is a poor design for drainage. While this type of heat exchanger is more efficient as pointed out by Qinghong Peng and Qungui Du [10, page 7] The melted water is difficult to remove between the fins and re-freezing of the coil can be a problem as explained by Ziqi Zhang, Wanyong Li, Junye Shi and Jiangping Chen [9, page 1].

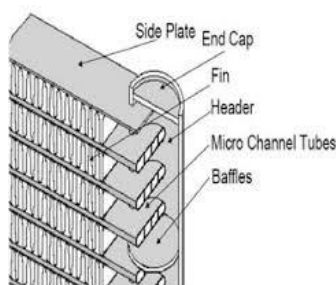


Image 2a. Detailed view of a MCHX



Image 2b. Overview of a MCHX

A solution for the drainage problem in EV heat pump evaporator coils is presented by Zhang et al [9] by using an evaporator coil with an optimized tube-and-fin construction. Zhang et al conclude that the optimized tube-and-fin heat exchanger can meet the demands in an EV in both heating and cooling mode and have much better drainage performance [9, page 9].

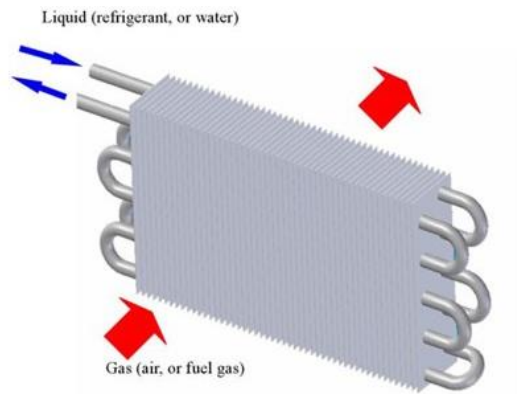


Image 3. Illustration of a tube-fin heat exchanger

3 Description of Vehicles in the Research

3.1 Drivetrain

The drivetrain used in the SLF-E and SLFA-E buses studied in this thesis is the Siemens ELFA drivetrain. The Siemens ELFA is a modular driveline system suitable for many applications, such as plane tractors, yachts, AGV vehicles, waste disposal vehicles and city buses. It can be used in a fully electric vehicle or can be implemented to a hybrid vehicle together with a diesel motor [14]. Recently VDL Bus & Coach has also been working together with DAF on an electric truck implementing a complete VDL high voltage system to the truck, the ELFA drivetrain being a part of it [15].

In the case of the VDL city buses included in this study, there are two variations of the ELFA system used, 1DB2016 and 1DB2022. The 1DB2016 is used in the SLF-E and has a max power of 160kw and a max torque of 2500Nm. It has one traction inverter and one set of 3 phase power for the engine. The more powerful 1DB2022 is used in the articulated SLFA-E and has a peak power of 240kW and a peak torque of 3600Nm [16]. It has two traction inverters and two three-phase inputs compared to its less powerful version. The 1DB2022 electric motor has also double coil windings [17].



Image 4a. Dismounted ELFA engine

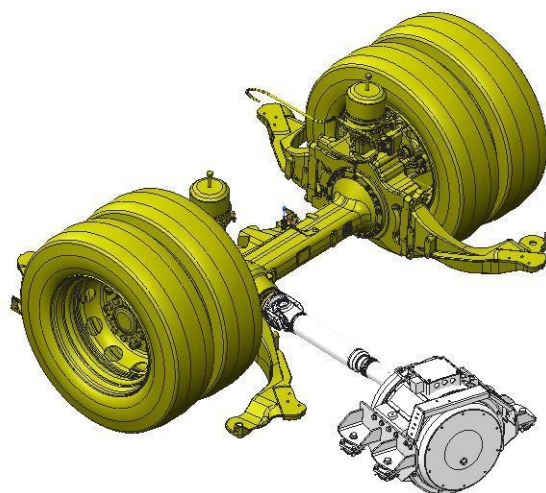


Image 4b. ELFA engine mounted to the drivetrain

3.2 Battery System

There are several battery pack options for the VDL electric city bus depending on the need for charging power or capacity, but the buses studied in this thesis all had similar battery pack specifications. At the time of writing this thesis, these packs were named HPHC (High power, high capacity) or HPMC (High power, medium capacity) by VDL.

The battery packs are positioned on top of the bus roof. Depending on the model of the bus, there are either 3 or 4 strings of batteries connected in parallel, for the SLF-E and SLFA-E respectively. Each string has two 300-volt packs, one on top of the other, making the total nominal voltage of the system 600V. Each pack has 70Ah of capacity and the complete capacity of the system is then 169kWh or 127kWh, depending on the model. Out of this capacity, 10% from the low side and 5% from the high side are not useable in order to maximize lifetime of the battery, making the useable capacity 144kWh or 108kWh.

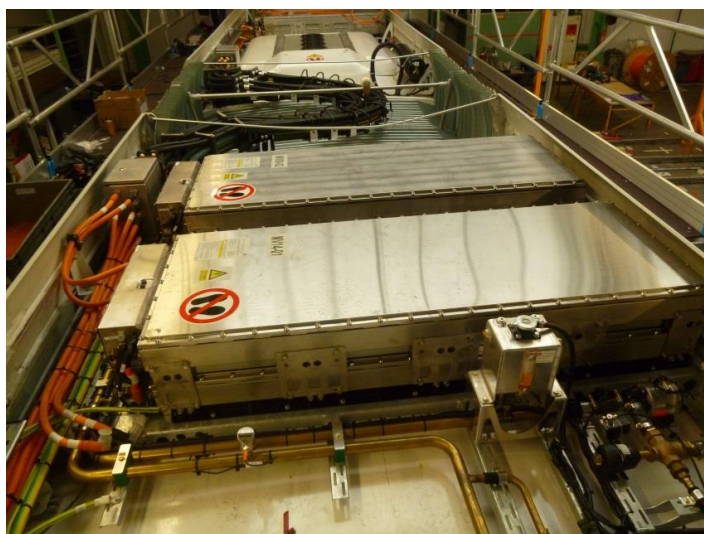


Image 5. Battery packs on the roof of an SLFA-E [18]

Each battery pack has seven smaller modules and each of these modules has twelve cells in series, seven in parallel. The packs are submerged in silicone oil illustrated by blue in image 6, and this silicone oil is acting as a heat transfer medium. The silicone oil can be cooled by the vehicles air conditioning system (heat pump) or heated by the heating system using traditional coolant which is pumped under a metal plate beneath the silicone oil.

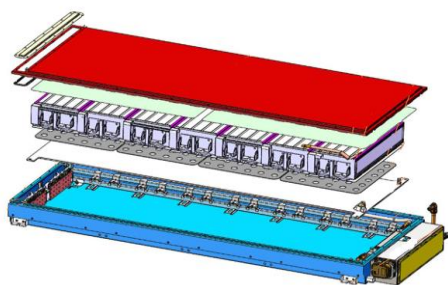


Image 6. Inside a battery pack

The supplier states the maximum and minimum operating conditions which the battery should be used at. The battery pack supplier also supplies the BMS and its software, so if the operating conditions are not met, the BMS will reduce power or disconnect the packs opening relays inside them. However, the software for the heating and cooling logic is made by VDL and actuated by another control unit than the BMS.

Coolant for the battery cooling circuit is controlled by a system of two valves, a heat exchanger and a coolant pump. Flow is controlled by the pump (image 7, 4) and either cooled by the AC unit (uninsulated pipes in the right lower corner, image 7) or heated by the heat exchanger (image 7, 3). The valve (image 7, 1) determines which circuit is followed, heating or cooling. The heat exchanger is heated by coolant water which flows through the brake resistor when the valve (image 7, 2) is opened. [18]. The heat exchanger between the battery heating circuit and the interior heating circuit is shown in figure 8.

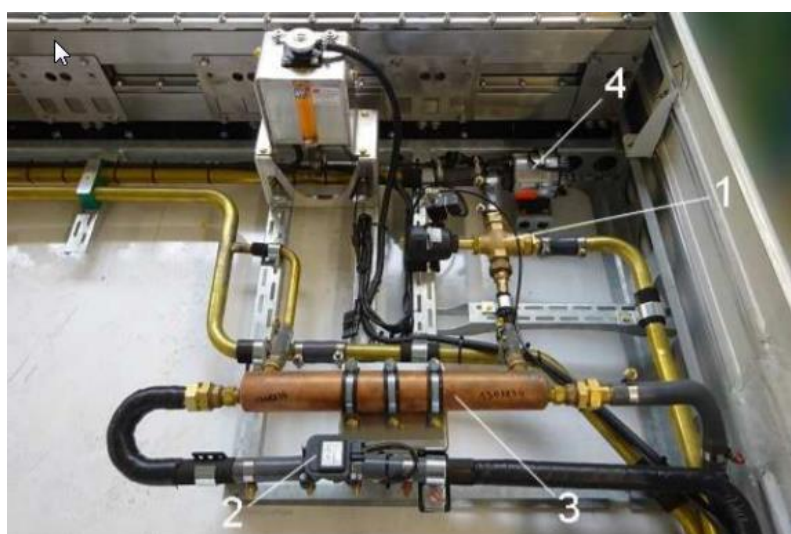


Image 7. Battery cooling circuitry [18]

If ambient temperature and cell temperature are low enough, the battery heating will be activated. However, if ambient temperature is above a certain value, the system will trust that the batteries will be warmed enough without heating. While charging the ambient temperature does not affect battery heating. Then the heating is activated only based on cell temperature. There is also a battery heat storage mode for even colder ambient temperatures which heats the batteries to a higher value during the final charge of the day, so that they would still retain some of that heat in the morning when the bus is started up again.

3.3 Climate System

3.3.1 Climate System Overview

In this chapter the heating functions of the climate systems are presented. Cooling functions of the system are not interesting for this thesis, and therefore, they will be left out.

SLF-E and SLFA-E have the following heat consumers:

- Heat exchanger for coolant for the battery cooling circuit (image 7, number 3)
- Separate coolant heating coils and refrigerant heating coils in the roof for heating the interior roof channel air for passengers
- Coolant heat radiator in the floor radiators for passenger space floor heating
- Coolant heat radiator for the driver
- Small coolant heating floor radiators for entrances to the bus

There are three heating systems in the SLF-E and SLFA-E that work together depending on several variables to warm up the passenger space and the batteries: heat pump, diesel preheater and a brake resistor. The primary system to heat up the passenger space is the heat pump thanks to its efficiency compared to heating using a resistor type heater, as discussed in chapter 2.4.2. The heat pump only heats the passenger space air from the roof channels though, and a brake resistor is used to warm up floor radiators and air for the driver, which are indicated by the box “HEATING” in figure 8. Below -10°C, the heat pump is turned off and the brake resistor is used for the roof heating as well.

The brake resistor is also used to preheat the bus in case it is plugged to a charger, taking the heating energy from the charger instead of the traction batteries when the bus goes to traffic in the morning.

A diesel preheater works in tandem with the brake resistor, sharing a coolant circuit with it. This is shown as the purple coolant circuit in figure 8. The diesel preheater makes it possible to preheat the bus in the morning in case it is not plugged to a charger and always takes over heating from the brake resistor when ambient temperatures are below 10°C, saving traction battery energy. It is also possible for customers to order a bus without the preheater, in case the vehicle should be 100% electric.

The so-called boost heating is another way to improve range. When the bus is connected to a charger and is fully charged, the boost heating software feature will allow the bus to be warmed electrically to a higher setpoint than normally used when driving. This will store heat energy to the interior air and materials, making the initial heating need lower when driving is started after being charged.

3.3.2 Thermo King Heat Pump

Like in many VDL diesel buses, VDL has chosen the climate system supplier Thermo King for its electric buses as well. The system used in the vehicles in this study have the E-700 series heat pumps, a system specifically designed for electric city buses.



Image 8. E700 series heat pump components [19]

The system uses a 400V AC scroll compressor and four separate solenoid valves to control the flow of refrigerant making the system either heat or cool. There are also two

solenoid valves to control cooling of the batteries using a coolant/refrigerant heat exchanger evaporator and one solenoid valve for defrosting the evaporator coils when the system is used for warming. See figures 5, 6 and 7 SV1-7 and blue components in image 8.

When cooling the interior, solenoid valves 1-4 are open to let high pressure gaseous refrigerant to the exterior coils, which act as an evaporator (see Figure 5). The batteries can be cooled both when the system is cooling or heating, using valves 5 or 6 depending on the battery cooling power need (Figure 5).

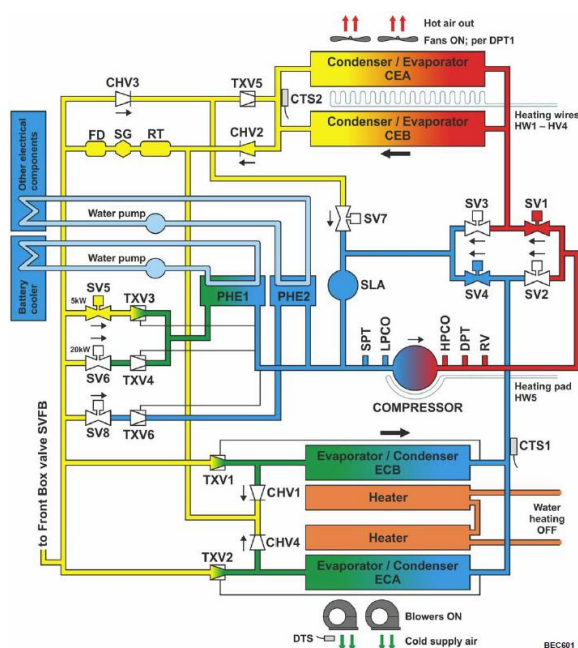


Figure 5. Heat pump cycle when cooling interior and batteries [18, page 29]

When heating the interior, valves 2-3 will be open to make the interior coils evaporators (Figure 6). The batteries can be cooled both when the system is cooling or heating, using valves 5 or 6 depending on the battery cooling power need (Figure 5).

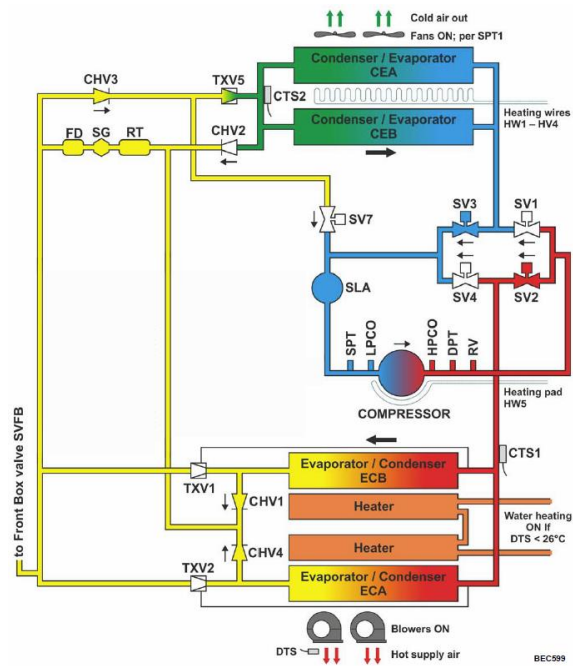


Figure 6. Heating cycle of the heat pump [18, page 30]

While heating the interior, defrosting of the exterior coils acting as evaporators can be done by opening solenoid valve 7 and closing 4. In this case, the cycle is reversed for a while and the exterior coils are warming as the refrigerant turns to liquid, but the liquid refrigerant is not directed to the interior coils to cool the interior, but to a suction line accumulator where it can turn into gas again for the compressor (Figure 7).

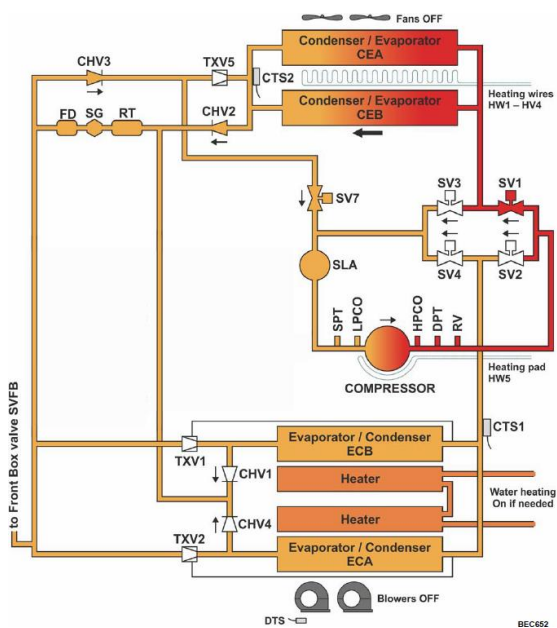


Figure 7. Defrosting cycle of the heat pump [18, page 34]

3.3.3 Brake Resistor

For heating the floor heating radiators and in some situations the roof heating radiators, VDL has chosen a so-called brake resistor. The brake resistor name originates from the fact that it is used to dissipate energy from the drive motor in case of regenerative braking with full battery. The brake resistor is a high-power DC powered resistor with a coolant heat exchanger around it. It is capable of producing a 60kW heating effect, so it is able to dissipate only a small amount of maximum regenerative braking. However, the second important role it has is to warm up the coolant circuit intended for heating, helping the heat pump electrically heat the bus or acting as the main electrical heater in colder temperatures than where the heat pump is specified to be used.



Image 9. Brake resistor [17, page 45]

The coolant circuit for heating is shown in Figure 8 in purple. This circuit includes all coolant heating radiators inside the bus, including floor heaters, roof heaters and drivers heating which are indicated by the box 'HEATING' in Figure 8. The brake resistor and the diesel preheater are both connected to this circuit. If the preheater is functioning correctly, the brake resistor is only used partially at above 10°C ambient temperatures while driving.

The pantographs on VDL electric buses are supplied by the manufacturer Shunk. It is moved up to its charging position and held there with a specific force by two springs and pulled down by an electric motor after charging. It is possible to fast charge using the pantograph, with a maximum power of 450kW. The pantograph is shown in Image 10.



Image 10. CCS charging plug and fast charging pantograph [17]

4 Testing and Research

4.1 Research Method

The basic idea in this thesis was to gather field data from buses, compare it with weather data of the corresponding days, try to find patterns and explanations for the patterns using literature research of similar technologies in similar weather. The research method was, therefore, quantitative with focus on correlation. There was only one group of similar buses to be studied, even though data from every bus was not available in every time period, so the correlation being researched was specifically between temperature and energy consumption. Since there were no reliable data on how much snow there was on the ground on each day and how rough the road surface was, only speculation was possible.

4.2 Data Gathering

Data were acquired from the buses in this research by ZF's OPENMATICS Bus Diagnostics system. OPENMATICS collects real time data from different systems such as powertrain or brakes. There is a Bosch onboard electronic unit with a sim card connected to the vehicle's FMS CAN bus that sends the data via internet to the user for diagnostic purposes. The user can then monitor the vehicle real time to see possible problems or faults and intervene in the situation early, or the data can be collected to a server, for example, for future analysis as was done in this thesis. [19]

There were limitations in the data. For various reasons the exterior and the interior temperatures by the report were not used and therefore the readings shown in the reports is not correct. Several buses show the same interior temperature and the exterior temperatures shown are not realistic. For this reason the data were more unreliable in general as public weather history was. For this reason, the comments of the data for individual buses in this thesis are unfortunately not much more than speculation. However, there are enough data to see trends that can be trusted more reliably.

The weather history was gathered from timeanddate.com. The five coldest periods of the winter were chosen from Location 1 and two from Location 2. Each period had data between two to five vehicles depending on how they were used at the time.

4.3 Reporting on the Data

The data gathered from OPENMATICS were stored as raw data that are vast and difficult to analyze. To make the data more readable, PowerBi application is used. PowerBi is a data analytics service from Microsoft. It offers data warehouse capabilities with interactive dashboards for reporting. With PowerBi, tailored reports are made by VDL from the OPENMATICS data that makes it possible to have a quick view of the data from several days or compare several values from a bus at the same time. For clarity, the data used in this thesis are shown only in the form of a PowerBi report.

4.4 Field Test

A research plan was made for the practical field tests for this thesis. However, as was mentioned earlier it was not possible to carry out the field test. However, the research plan could be relevant for future field testing and even with possible new electric bus models in the future. For this reason, the plan is presented in this chapter

The research would have been an addition to the winter test carried out in Jokkmokk in January 2018. The scope of this research was narrowed to power consumption optimization of the buses.

The goal of this research was to investigate the current performance of the Citea SLF-E and SLFA-E in the Nordic conditions power consumption wise. Based on the acquired data, the goal was to provide suggestions for improvements to optimize the power consumption and range in climate conditions of the Nordic winter in a temperature range from -10°C down to -35°C. The suggested improvements could be either software strategy or hardware.

The test could be carried out by transporting a demo bus or a bus still under implementation period to the test site.

The following different situations were seen interesting as a controlled test for this research:

1. When the bus goes in line already warm, after being stored in a warm hall.
2. When the bus goes in line already warm, after being plugged to a charger.
3. When the bus goes in line cold, but heated by a diesel preheater.
4. When the bus has to be completely heated up by itself when leaving for line.

All the situations should be tested on the same route, simulating urban traffic.

The following subjects were planned to be investigated in each situation above:

- Battery temperature.
- Energy consumption of the driveline. Logs from Siemens Siadis diagnostic program.
- Energy consumption of the brake resistor.
- Coolant temperature from all sensors included in the bus.
- Temperature of the interior. For this measurement, additional sensors and a monitoring system should be used for more accurate measurement than just the ones already present in the systems of the bus. The same setup as at the winter test in 2018 should be used.

From changes of the energy consumption of the brake resistor and the temperature changes of the measured places, calculations will be made for energy consumption of interior heating and battery heating.

Outside the controlled test, the following topics were planned to be investigated for this research:

- How much time would it take to heat up the bus with the wall charger or pantograph plugged?
- How long would the bus stay warm after pre-heating and without driving?
- What is the influence of opening doors on passenger space temperature changes and energy consumption of the brake resistor? Three situations should be recorded: Low, medium and high amount of stops and opening of the doors.
- Possibility to try a simple isolation also on one battery string to see if there is any benefit in certain situations.

Testing at winter test location:

Schedule for day 1:

- Bus leaves from a warm storage.
- Test driving test route until warm.
- Test driving test route with stopping every 5 minutes and opening only one door at the time (very light traffic).

- Test driving test route with stopping every 3 minutes and opening two doors at the time (moderate traffic).
- Test driving test route with stopping every 1 minute and opening all doors at the same time (very heavy urban traffic).
- Recording SOC and trip meter.
- Measuring temperatures while the bus cools down to see how long it takes.

Schedule for day 2:

- Heating the bus with the charger plugged.
- Measuring time to heat up the bus completely while plugged.
- Test driving test route until warm.
- Test driving test route with stopping every 5 minutes and opening only one door at the time (very light traffic).
- Test driving test route with stopping every 3 minutes and opening two doors at the time (moderate traffic).
- Test driving test route with stopping every 1 minute and opening all doors at the same time (very heavy urban traffic).
- Recording SOC and trip meter.

Day 3:

- Starting driving when cold, letting the diesel heater heat up the bus.
- Driving until warm.
- The same test routines as days 1 and 2.

Day 4:

Starting driving when cold but disabling diesel preheater, only heating with electricity.

- Driving until warm.
- The same test routines as days 1 and 2.

5 Results

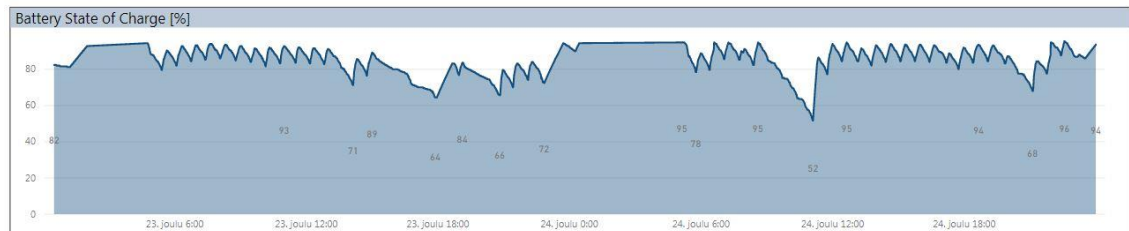
The complete data gathered from ZF OPENMATICS for this thesis can be seen in Appendix 1.

5.1 Location 1 23-24 December 2018

The first interesting period of the winter was 23-24 December 2018 in Location 1. Temperatures ranged from -6°C to -13°C. Data from three buses were available from that time.

Consumption of all buses during this period was good, never even closely reaching 2 kWh per kilometer. The chargers were clearly working well since it was possible to keep SOC above 50% and most of the time around 80%.

Most kilometers were driven with bus 1. Driveline consumption was relatively low, affected by a good amount of recuperation and low standing time with the main switch on.



Graph 8. SOC curve of bus 1 during 23-24.12.2018

470 Distance Travelled [km]	1,69 Average Consumption [kWh/km]	0,47 Recuperation [kWh/km]	0,62 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 4 287,00	Battery Consumption [kWh] 794 Total Consumption 292,26 Climate Consumption	Recuperation [kWh] 218,85 Total Recuperation	Temperature (C) 3,05 Average Outside Temperature 15 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 12,05 Main Switch On 18,31 E-Drive On 25,79 Driving			

Table 3. Consumption overview of bus 1 during 23-24 December 2018

5.2 Location 1 16-21 January 2019

The average speeds were slightly slower than during the first recorded period, indicating more bus stops and traffic in general. Also while observing the SOC it is very clear that all chargers were not available or there was trouble using them and the state of charge dropped frequently below 50% in all buses. A relationship could be seen in the amount of time the main switch and E-Drive had been on and a higher driveline consumption.

Bus 2 had most kilometres driven during this time. Recuperation was rather low, which affected driveline consumption negatively. Most likely this was caused by a driver with less experience from economic driving. The effect of standing with the main switch on can be seen when comparing the driveline consumption of bus 2 in Table 4 with 1 from table 5.



Graph 9. SOC curve of bus 2 during 16-21 January 2019

874 Distance Travelled [km]	1,91 Average Consumption [kWh/km]	0,37 Recuperation [kWh/km]	0,61 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 5 405,00	Battery Consumption [kWh] 1669 Total Consumption	Recuperation [kWh] 324,96 Total Recuperation	Temperature (C) -0,50 Average Outside Temperature
Averages of Velocity [km/h] 13,91 Main Switch On 18,63 E-Drive On 23,62 Driving	531,03 Climate Consumption		8 Keskiarvo: HVAC_TEMP_InsideTe...

Table 4. Consumption overview of bus 2 during 16-21 January 2019

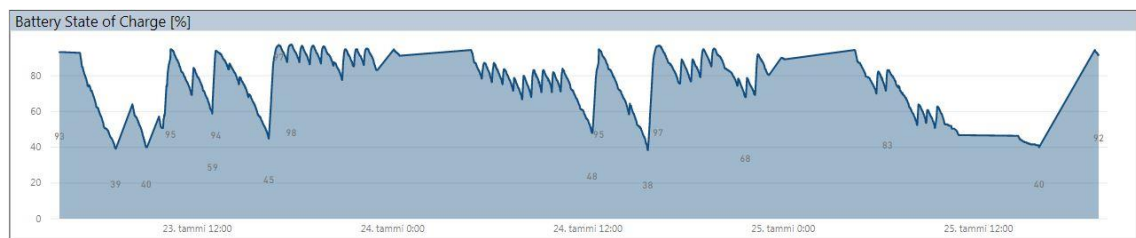
199 Distance Travelled [km]	2,08 Average Consumption [kWh/km]	0,51 Recuperation [kWh/km]	0,56 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 6 338,00	Battery Consumption [kWh] 414 Total Consumption	Recuperation [kWh] 100,50 Total Recuperation	Temperature (C) -0,50 Average Outside Temperature
Averages of Velocity [km/h] 5,89 Main Switch On 14,23 E-Drive On 24,19 Driving	111,31 Climate Consumption		8 Keskiarvo: HVAC_TEMP_InsideTe...

Table 5. Consumption overview of bus 1 during 16-21.1.2019

5.3 Location 1 22-27 January 2019

This time period was not particularly cold but provided a good average during a mild winter week, with temperatures around -5°C on average. Data from four buses were available.

Bus 2 was driven the most during this time. Fast charging was available, but not used at every end stop. An interesting fact was that even though the weather was relatively warm, climate consumption was similar with the colder periods as can be seen in Table 6.



Graph 10. SOC curve of bus 2 during 22-27 January 2019

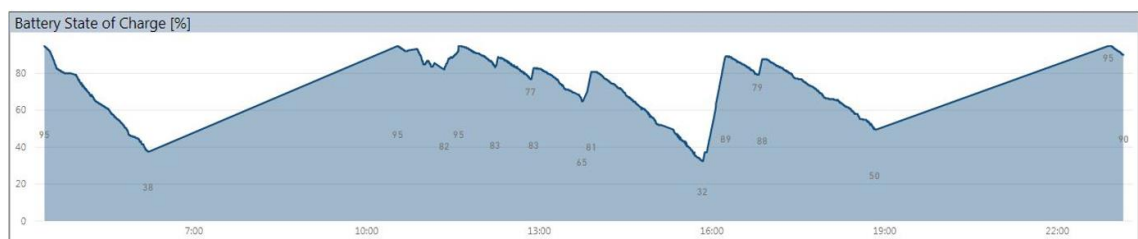
608 Distance Travelled [km]	1,94 Average Consumption [kWh/km]	0,44 Recuperation [kWh/km]	0,63 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 6 013,00	Battery Consumption [kWh] 1176 Total Consumption 384,24 Climate Consumption	Recuperation [kWh] 267,14 Total Recuperation	Temperature (C) 3,39 Average Outside Temperature 15 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 14,30 Main Switch On 17,67 E-Drive On 23,81 Driving			

Table 6. Consumption overview of bus 2 during 22-27 January 2019

5.4 Location 1 29-31 January 2019

This time period was a good comparison to the previous milder one. Bus 4 had average consumptions while bus 3 clearly had problems. It should be investigated in the workshop records, if there was an issue with the system, especially the diesel pre-heater.

Bus 3 had driven the most during a single day on 31 January with a total of 145km. Both fast and slow charging were used. Climate consumption was a record for this thesis, reaching 0.92kWh/km as can be seen in Table 7. This gives a good worst case scenario reading which can be referred to in the future, for example when doing calculations for a new project.



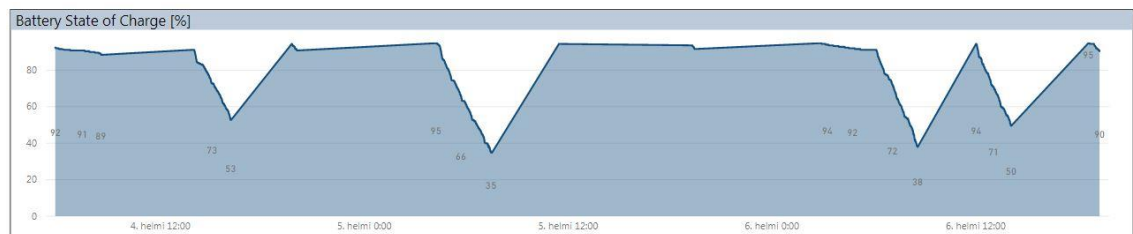
Graph 11. SOC curve of bus 3 during 31 January 2019

145 Distance Travelled [km]	2,35 Average Consumption [kWh/km]	0,44 Recuperation [kWh/km]	0,92 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 9 850,00	Battery Consumption [kWh] 342 Total Consumption 133,46 Climate Consumption	Recuperation [kWh] 63,68 Total Recuperation	Temperature (C) 3,75 Average Outside Temperature 10 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 14,94 Main Switch On 18,39 E-Drive On 24,21 Driving			

Table 7. Consumption overview of bus 3 during 31 January 2019

5.5 Location 1 3-6 February 2019

Data from three buses were available from this time period. The weather was at times very cold but also at times around 0°C. Again bus 3 had a higher climate consumption than the other two. Fast charging was clearly not available at all during this time. Otherwise consumption stayed at almost exactly 2 kWh/km except for 3. Most kilometers were driven with bus 2. Data from this bus can be seen in Graph 12 and table 8. Overall the data from this period did not give much more insight on anything particular, but can be used for statistical purposes.



Graph 12. SOC curve of bus 2 during 3-6 February 2019

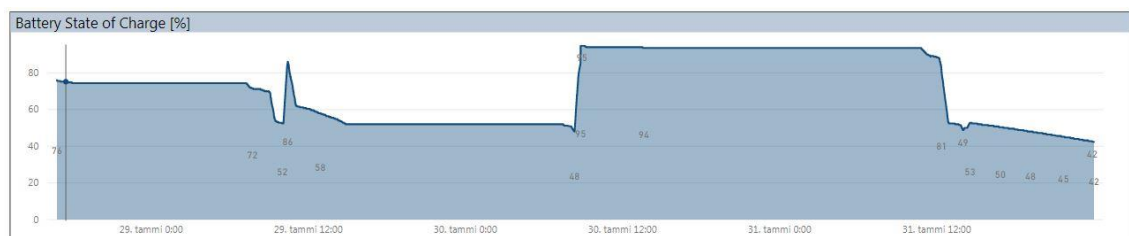
166 Distance Travelled [km]	2,01 Average Consumption [kWh/km]	0,44 Recuperation [kWh/km]	0,54 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 6 180,00	Battery Consumption [kWh] 335 Total Consumption 90,43 Climate Consumption	Recuperation [kWh] 72,91 Total Recuperation	Temperature (C) 7,42 Average Outside Temperature 14 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 10,67 Main Switch On 15,91 E-Drive On 23,21 Driving			

Table 8. Consumption overview of bus 2 during 3-6 February 2019

5.6 Location 2 28-31.1.2019

Temperatures in Location 2 were higher than average during the winter, which was a risk that was acknowledged when planning this thesis. This week was the coldest according to the data with the highest temperatures around -5°C. The 29th and 30th February were the two coldest days in this location when the temperature dropped to around -10C.

Bus 6 had driven 95 kilometers which was the most during this period. Luckily the most kilometres were driven on 29th and 31th of February, which were both among the coldest days that were measured. The bus had been standing long with only the main switch on, which might have biased the driveline consumption. As shown in Table 9, the average speed was higher than in other buses during this time and most likely for that reason the climate consumption per kilometer was lower. This can be seen in the other buses at this location as well.



Graph 13. SOC curve of bus 6 during 29-31 January 2019

95 Distance Travelled [km]	1,71 Average Consumption [kWh/km]	0,29 Recuperation [kWh/km]	0,37 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 247,00	Battery Consumption [kWh] 163 Total Consumption 35,46 Climate Consumption	Recuperation [kWh] 27,71 Total Recuperation	Temperature (C) 5,19 Average Outside Temperature 12 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 3,38 Main Switch On 8,26 E-Drive On 40,90 Driving			

Table 9. Consumption overview of bus 6 during 29-31 January 2019

5.7 Location 2 3-6 February 2019

Data available were not very useful from this period. There was no driving during the coldest days and the overall amount of driving was low. This was included in the thesis anyway to have more variety and comparison with the other periods. 10 was the bus with the most kilometers during this period. It had also the lowest overall consumption of all buses included in this study that had been driven on the road with its climate system in use. Data from this bus are shown in Graph 14 and table 10.



Graph 14. SOC curve of bus 10 during 3-6 February 2019

66 Distance Travelled [km]	1,19 Average Consumption [kWh/km]	0,25 Recuperation [kWh/km]	0,25 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 72,00	Battery Consumption [kWh] 79 Total Consumption	Recuperation [kWh] 16,67 Total Recuperation	Temperature (C) 7,42 Average Outside Temperature
Averages of Velocity [km/h] 3,24 Main Switch On 7,23 E-Drive On 38,03 Driving	16,34 Climate Consumption		14 Keskiarvo: HVAC_TEMP_InsideTe...

Table 10. Consumption overview of bus 10 during 3-6 February 2019

6 Conclusions

6.1 Data Analysis

This thesis shows that the consumption of the electrical part of the climate system, the heat pump and the brake resistor, was remarkably steady and reliable during all the periods included in this research. On average during the coldest days, the consumption does not rise much higher than 0.6 kWh/km on line traffic. Software for controlling the bus heating setpoint seems well thought and the diesel pre-heater was able to take care of higher heating needs in colder ambient temperatures. The only clear exception for this was bus 3 during 3-6 February. It had 50% larger consumption than the rest. It would be worth investigating in the workshop records, if this bus had a problem with the diesel preheater. More obviously with higher average speeds, as seen during the implementation period in Location 2, climate consumption drops since higher speeds mean less running time per kilometer of the climate system.

Driveline consumptions seemed to fluctuate significantly in different conditions. Most notably there was correlation between low average speed with the main switch on, in other words the vehicle had been standing for long with only the main switch turned on. The isolated powertrain energy usage can be calculated by deducting the climate consumption and adding total regeneration to the driveline consumption, for example, for bus 4 on 31 January 2019 at location 1:

- Average consumption 2.01 kWh/km
- Recuperation 0.48 kWh/km
- Climate consumption 0.62 kWh/km

$$2.01 - 0.62 + 0.48 = 1.87$$

To analyze the correlation, a Pearson correlation coefficient can be calculated with the following function:

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}} \quad (6)$$

Where x and y are value arrays for the main switch on time and driveline consumption, and \bar{x} and \bar{y} are sample means of the two array values. The correlation coefficient for the main switch on average speed and driveline consumption was -0.479 for buses in location 1, which is a moderate negative correlation when conditions, for example road snow conditions, were not known. With big fleets it is good to acknowledge that even if there is no problem with range, leaving the main switch on without a reason will influence the overall electricity usage of the company.

Regeneration while driving in line was generally between 0.4 and 0.5 kWh/km. This emphasizes the importance of economic driving to improve the reduced range during winter. It makes most sense to compare regenerations in location 1 in actual traffic. The highest average regeneration during a period of driving in location 1 was 0.53 kWh/km and lowest 0.37 kWh/km. This gives a 0.16 kWh/km difference which at an average consumption between 1.6-2.1 kWh/km constitutes about 7%-10% increased energy consumption from the lowest to the highest recorded value.

6.2 Following Work

Since the climate data were not very accurate, it would be interesting to continue gathering similar consumption reports from the buses during the next winter with more detailed weather descriptions from each location, most importantly the amount of snow on the road due to reason explained in chapter 2.3. Other important variables that should be measured are the door usage during bus stops and vehicle load, which could possibly be measured with a can logger directly from the vehicle. It would also be good to have the interior temperature or perhaps passenger complaints from the same period to see how comfortably the climate system is performing.

Well planned testing in truly arctic conditions is still a relevant test during writing of this thesis. The Nordic winter can surprise and after the research in this thesis similar buses have started driving in colder locations. Extensive testing as proposed in chapter 4.4 would still help in preparing for unforeseeable risks that below -30°C temperatures could pose.

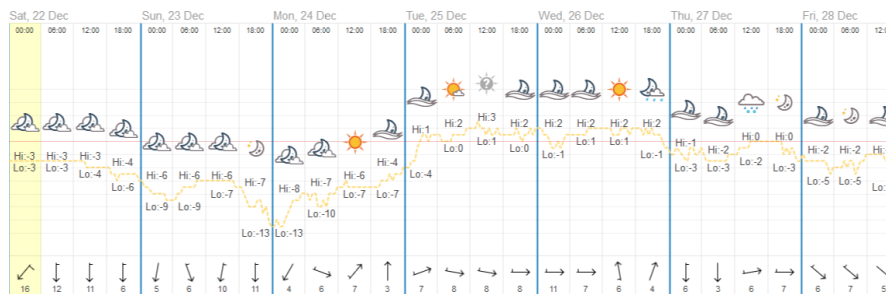
References

- 1 Asma Mohamad Aris, Bahman Shabani. 2017. An experimental study of a lithium ion cell operation at low temperature conditions. Elsevier.
- 2 Shanshan Guo, Yun Liu and Lin Li. 2017. Study on the Performance of Lithium-Ion Batteries at Different Temperatures. Atlantis press.
- 3 Qianqian Liu, Chunyu Du, Bin Shen, Pengjian Zuo, Xinqun Cheng, Yulin Ma, Geping Yin and Yunzhi Gao. 2016. Understanding undesirable anode lithium plating issues in lithium-ion batteries. RSC Advances.
- 4 Wong, J. Y. 2001. Theory of ground vehicles. John Wiley & Sons, Inc.
- 5 S.K. Clark and R.N. Dodge. 1979. Handbook of rolling resistance for pneumatic tires.
- 6 Arto Haakana, Juhani Laurikko, Robert Granström, Rolf Hagman. 2013. Assessing range and performance of electric vehicles in Nordic driving conditions – End of Project Report. Nordic energy research.
- 7 Heat Pump - an overview. 2012 Web document. ScienceDirect <<https://www.sciencedirect.com/topics/earth-and-planetary-sciences/heat-pump>>
- 8 G.F. Hundy, A.R. Trott, T.C. Welch, 2016. Refrigeration, air conditioning and heat pumps. Elsevier.
- 9 Ziqi Zhang, Wanyong Li, Junye Shi, Jiangping Chen. 2016. A Study on Electric Vehicle Heat Pump Systems. Energies.
- 10 Qinghong Peng and Qungui Du. 2015. Progress in Heat Pump Air Conditioning Systems for Electric Vehicles - A Review. Energies.
- 11 Radu Musat and Elena Helerea. 2010. Characteristics of the PTC Heater Used in Automotive HVAC Systems. Conference paper. IFIP Advances in Information and Communication Technology.
- 12 Tanja Kallio. 2018. Lithium Ion Batteries for Metropolia. Lecture material. Aalto University.
- 13 Celina Mikolajczak, Michael Kahn, Kevin White, Richard Thomas Long. 2011. Lithium-Ion Batteries Hazard and Use Assessment.
- 14 ELFA: Zero emissions – the cost-effective and smart way. 2015. Product brochure. Siemens AG.
- 15 VDL Groep and DAF present electric truck. 2018. VDL Groep.
- 16 Aiming for Zero. 2018. Product brochure. VDL Groep.

- 17 Basic mechanic level 2 V2. 2019. Training Document. VDL Bus & Coach.
- 18 Thermo King maintenance manual TK 61469-3. Thermo King.
- 19 Diagnostics for Buses. Web document. ZF Friedrichshafen AG. <<https://aftermarket.zf.com/go/en/openmatics/diagnostics/diagnostics-for-buses/>>
- 20 Weatherspark.com.<<https://weatherspark.com/m/85356/2/Average-Weather-in-February-in-Jokkmokk-Sweden>>,<<https://weatherspark.com/m/51381/2/Average-Weather-in-February-in-Amsterdam-Netherlands>>
- 21 Air - Density, Specific Weight and Thermal Expansion Coefficient at Varying Temperature and Constant Pressures. Web document. Engineering ToolBox. <https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html>
- 22 Second law of thermodynamics. Web document. Wikipedia. <https://en.wikipedia.org/wiki/Second_law_of_thermodynamics>

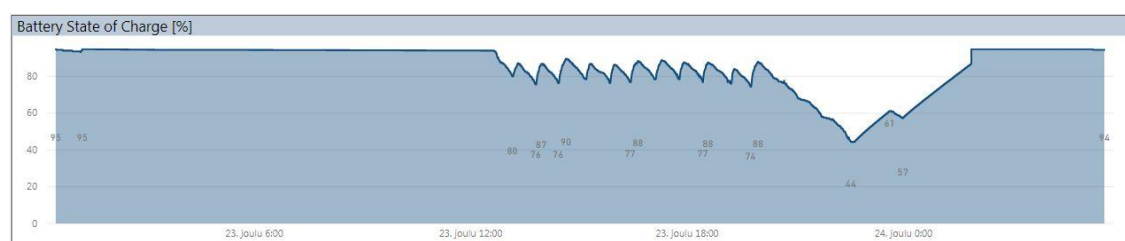
Complete results

Location 1 23-24 December 2018



The first interesting period of the winter was 23-24 in Location 1. Temperatures ranged from -6°C to -13°C. Data from three buses were available from that time.

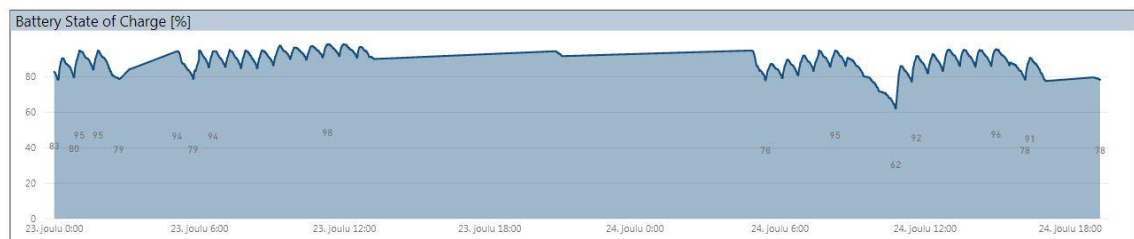
Bus 4



147 Distance Travelled [km]	1.76 Average Consumption [kWh/km]	0.53 Recuperation [kWh/km]	0.61 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 3 357,00	Battery Consumption [kWh] 259 Total Consumption 89,44 Climate Consumption	Recuperation [kWh] 78,22 Total Recuperation	Temperature (C) 3,05 Average Outside Temperature 15 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 8,36 Main Switch On 18,81 E-Drive On 25,42 Driving			

Bus 4 had driven from noon 23th until almost midnight. Climate consumption was very high, but driveline consumption was still moderate at 1.15 kWh/km. The system did not need to reduce heating power.

Bus 3



334 Distance Travelled [km]	1,65 Average Consumption [kWh/km]	0,45 Recuperation [kWh/km]	0,52 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 4 785,00	Battery Consumption [kWh] 551 Total Consumption	Recuperation [kWh] 149,31 Total Recuperation	Temperature (C) 3,05 Average Outside Temperature
Averages of Velocity [km/h] 14,31 Main Switch On 20,06 E-Drive On 26,92 Driving	175,09 Climate Consumption		15 Keskiarvo: HVAC_TEMP_InsideTe...

This bus had more kilometres driven and a higher average speed than 4. The climate consumption was slightly lower most likely because the bus was not driving 23th afternoon and the following night, which was the coldest part of this period.

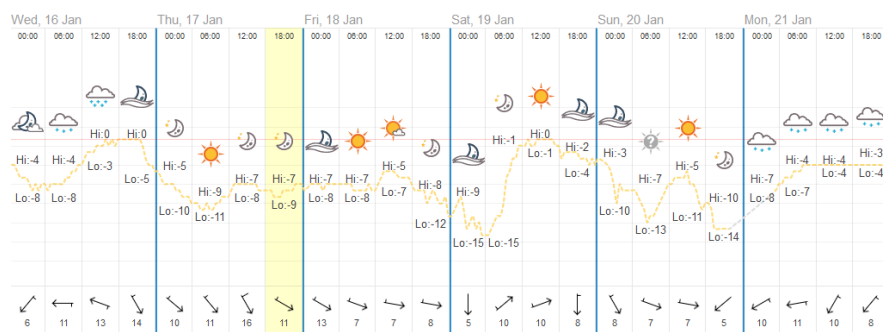
Bus 1



470 Distance Travelled [km]	1,69 Average Consumption [kWh/km]	0,47 Recuperation [kWh/km]	0,62 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 4 287,00	Battery Consumption [kWh] 794 Total Consumption 292,26 Climate Consumption	Recuperation [kWh] 218,85 Total Recuperation	Temperature (C) 3,05 Average Outside Temperature 15 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 12,05 Main Switch On 18,31 E-Drive On 25,79 Driving			

This bus had the most kilometers and the highest average speed among the three. The bus was driving constantly during the period, except between midnight and 5am 24th. Despite high climate consumption, overall consumption was very moderate.

Location 1 16-21 January 2019



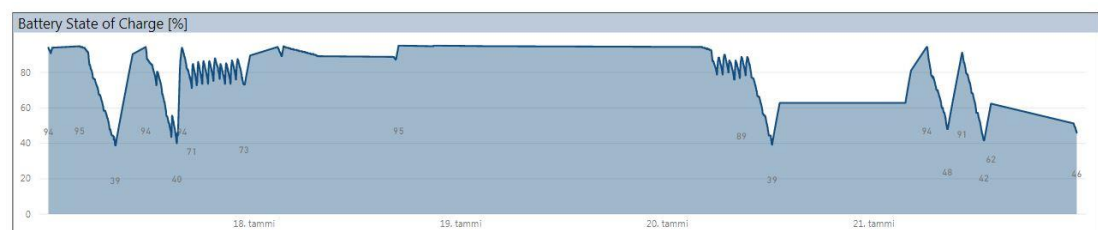
During this period there were a few quite cold days, 20th being the coldest, but also high fluctuation of temperatures which should be taken in account when reading results. Data were available from four buses, some with relatively high kilometres driven.

Bus 2



This bus had most kilometers from all four during this period. Climate consumption was steady as expected. Compared to the earlier period, Recuperation was significantly lower perhaps revealing an inexperienced driver. This explains the slightly higher consumption than seen before.

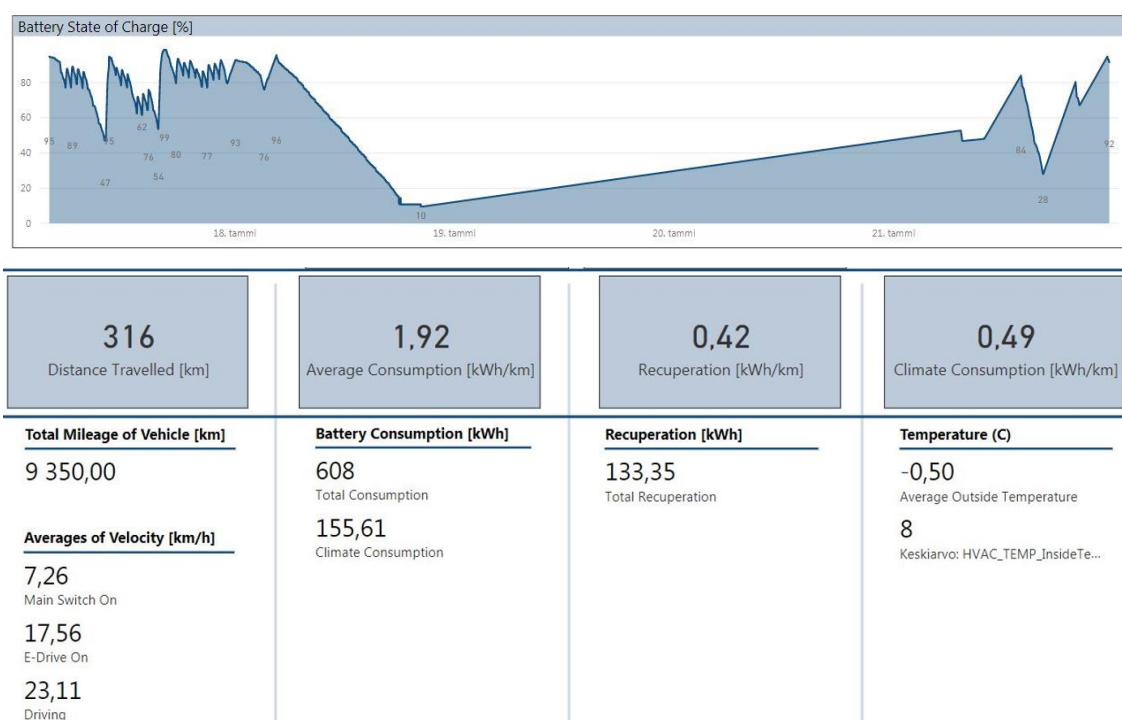
Bus 4



416 Distance Travelled [km]	1,79 Average Consumption [kWh/km]	0,45 Recuperation [kWh/km]	0,48 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 7 554,00	Battery Consumption [kWh] 745 Total Consumption 199,46 Climate Consumption	Recuperation [kWh] 187,11 Total Recuperation	Temperature (C) -0,50 Average Outside Temperature 8 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 9,66 Main Switch On 18,02 E-Drive On 23,90 Driving			

The bus had a slightly lower climate consumption. No conclusions can be made on why exactly, since based on the SOC it did not avoid driving on the coldest days.

Bus 3



The bus was driving 17th, 18th and 21th and so avoided the coldest times which might be the cause for lower climate consumption than bus 2, for example.

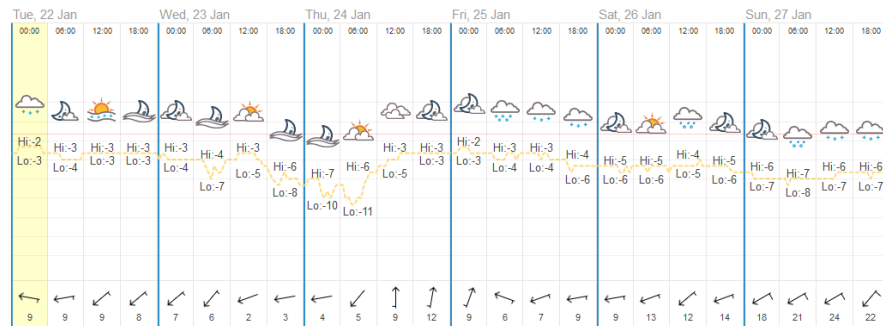
Bus 1



199 Distance Travelled [km]	2,08 Average Consumption [kWh/km]	0,51 Recuperation [kWh/km]	0,56 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 6 338,00	Battery Consumption [kWh] 414 Total Consumption 111,31 Climate Consumption	Recuperation [kWh] 100,50 Total Recuperation	Temperature (C) -0,50 Average Outside Temperature 8 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 5,89 Main Switch On 14,23 E-Drive On 24,19 Driving			

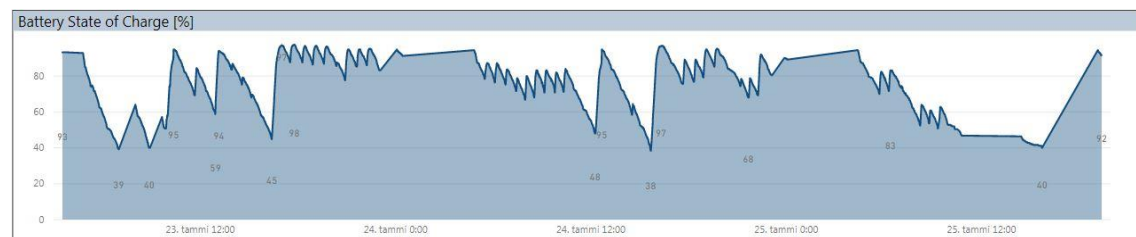
The bus had a noticeably higher average consumption than the rest. This is not explained by high climate consumption or low recuperation. It also seems like the bus was not fast charged at all during the time. Low average velocity with E-Drive and especially main switch show that the bus had been standing a lot during this time, which explains the high drivetrain consumption.

Location 1 22-27 January 2019



This time period was not particularly cold but provided a good average during a mild winter week. Data from four buses were available.

Bus 2



608 Distance Travelled [km]	1,94 Average Consumption [kWh/km]	0,44 Recuperation [kWh/km]	0,63 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 6 013,00	Battery Consumption [kWh] 1176 Total Consumption 384,24 Climate Consumption	Recuperation [kWh] 267,14 Total Recuperation	Temperature (C) 3,39 Average Outside Temperature 15 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 14,30 Main Switch On 17,67 E-Drive On 23,81 Driving			

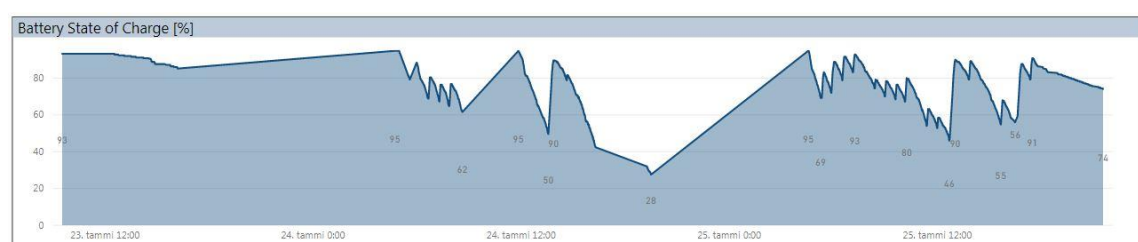
The SOC changes show that fast charging was available, but it was not used at all end stops. SOC levels were near 80% most of the time. It is interesting to notice that climate consumption was relatively high even in such mild temperatures.

Bus 4



This bus was only driving on the 23th and 24th of January. The same as from bus 2 can be said in case of this bus. A lower average velocity during main switch on explains the higher consumption.

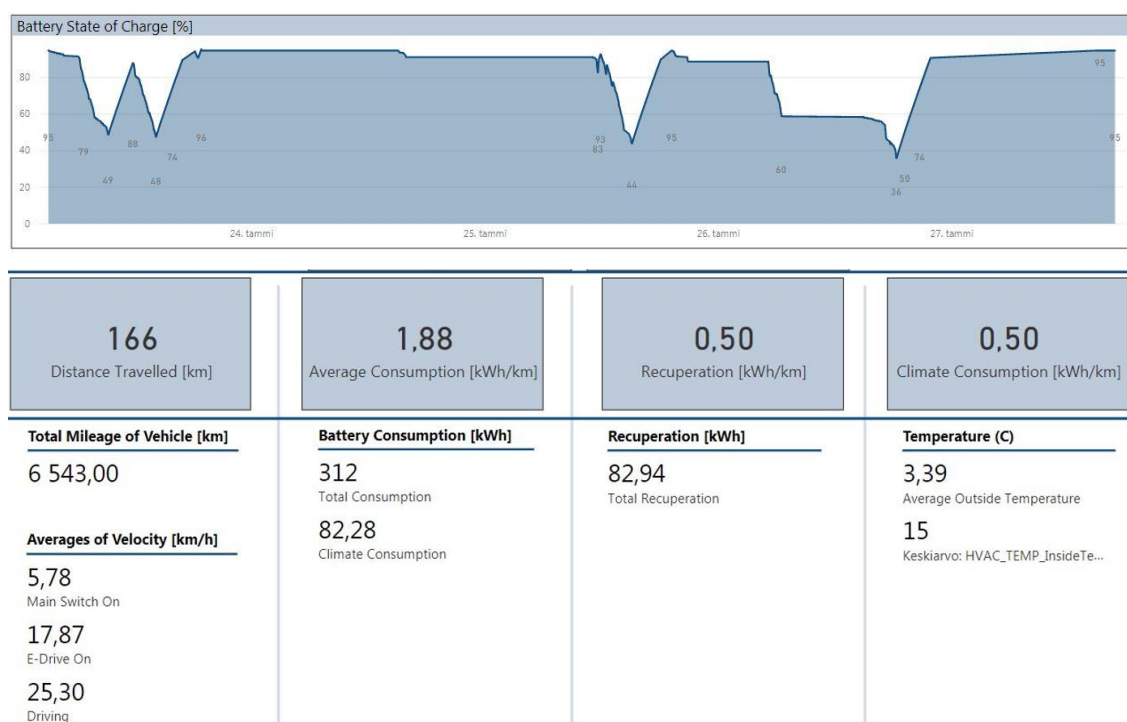
Bus 3



300 Distance Travelled [km]	2,30 Average Consumption [kWh/km]	0,43 Recuperation [kWh/km]	0,90 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 9 650,00	Battery Consumption [kWh] 688 Total Consumption 270,81 Climate Consumption	Recuperation [kWh] 129,10 Total Recuperation	Temperature (C) 3,39 Average Outside Temperature 15 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 11,35 Main Switch On 15,72 E-Drive On 22,58 Driving			

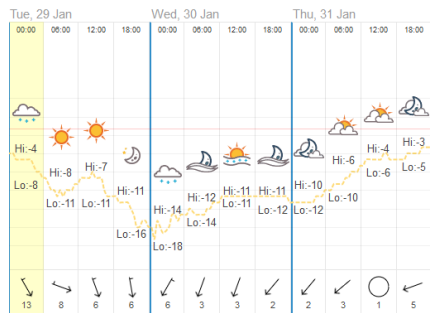
This bus had unusually high climate consumption that was not explained by any factor seen with previous buses. The overall average speed was lower than other buses, which could indicate more stops. There was almost no driving on the 23th of January.

Bus 1



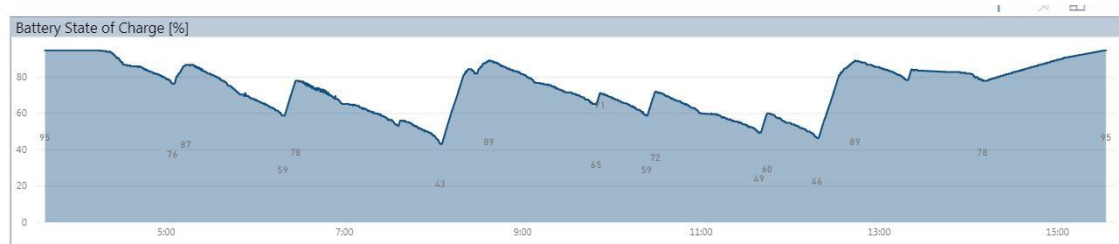
Here again, a low main switch on time can be related to a high powertrain consumption, even though the driver did perform well using regeneration. It also seems like the bus was not fast charged at all.

Location 1 29-31 January 2019



This time period was a good chance to get some data from a colder day. Unfortunately, there were data only from two buses. To get more accurate information, this time the data were split for each day per bus.

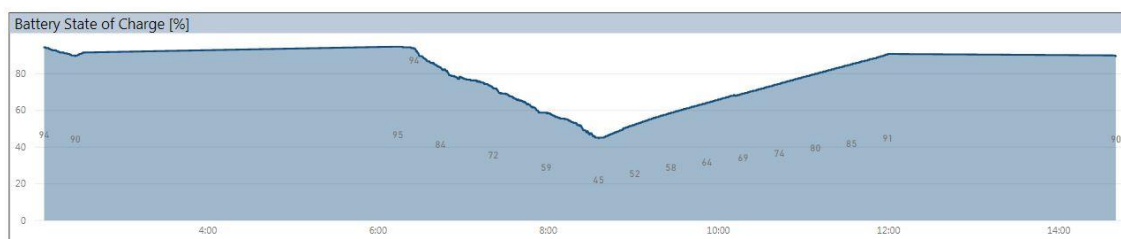
Bus 4 29 January



137 Distance Travelled [km]	2,00 Average Consumption [kWh/km]	0,44 Recuperation [kWh/km]	0,60 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 8 119,00	Battery Consumption [kWh] 274 Total Consumption 82,26 Climate Consumption	Recuperation [kWh] 60,26 Total Recuperation	Temperature (C) 3,76 Average Outside Temperature 14 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 12,75 Main Switch On 18,32 E-Drive On 23,85 Driving			

Even for a cold day, the consumptions were very average.

Bus 4 30 January 2019



46 Distance Travelled [km]	1,88 Average Consumption [kWh/km]	0,48 Recuperation [kWh/km]	0,60 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 8 165,00	Battery Consumption [kWh] 86 Total Consumption 27,46 Climate Consumption	Recuperation [kWh] 22,07 Total Recuperation	Temperature (C) 4,31 Average Outside Temperature 14 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 7,37 Main Switch On 17,37 E-Drive On 25,87 Driving			

The same can be said for this day. Even though it was one of the coldest days, the climate consumption was average. The higher average speed contributed to a slightly smaller drivetrain consumption. Main switch on average velocity was low, but so were total kilometres so this did not have a big influence on consumption. No fast charging was used.

Bus 3 30 January 2019



55 Distance Travelled [km]	2,38 Average Consumption [kWh/km]	0,40 Recuperation [kWh/km]	0,95 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 9 705,00	Battery Consumption [kWh] 131 Total Consumption	Recuperation [kWh] 21,79 Total Recuperation	Temperature (C) 4,31 Average Outside Temperature
Averages of Velocity [km/h] 9,54 Main Switch On 13,79 E-Drive On 22,51 Driving	52,12 Climate Consumption		14 Keskiarvo: HVAC_TEMP_InsideTe...

The bus had been driven little this day and it can clearly be seen that it was moved in the depot or the power was on and off a few times at around 15.00. The standstill heating, the consumption of the initial heating compared to the few kilometres actually driven could explain the unusually high climate consumption, but not completely.

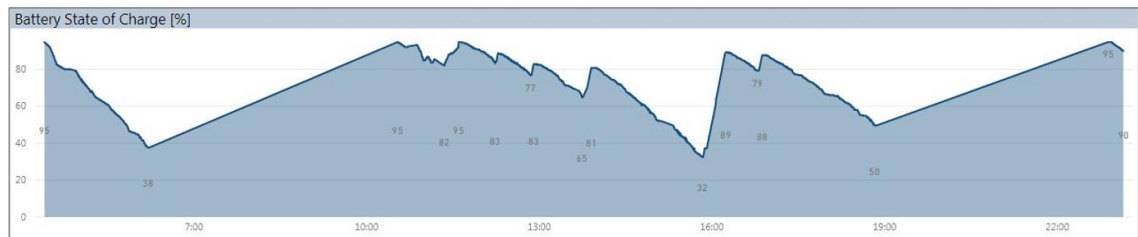
Bus 4 31 January 2019



81 Distance Travelled [km]	2,01 Average Consumption [kWh/km]	0,48 Recuperation [kWh/km]	0,62 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 8 245,00	Battery Consumption [kWh] 163 Total Consumption	Recuperation [kWh] 38,85 Total Recuperation	Temperature (C) 3,75 Average Outside Temperature
Averages of Velocity [km/h] 10,14 Main Switch On 16,51 E-Drive On 23,47 Driving	49,92 Climate Consumption		10 Keskiarvo: HVAC_TEMP_InsideTe...

Again, this bus had a very stable consumption from all perspectives.

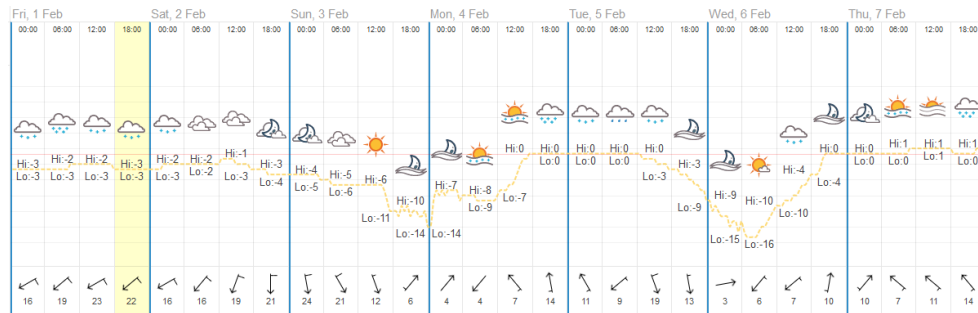
Bus 3 31 January 2019



145 Distance Travelled [km]	2,35 Average Consumption [kWh/km]	0,44 Recuperation [kWh/km]	0,92 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 9 850,00	Battery Consumption [kWh] 342 Total Consumption 133,46 Climate Consumption	Recuperation [kWh] 63,68 Total Recuperation	Temperature (C) 3,75 Average Outside Temperature 10 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 14,94 Main Switch On 18,39 E-Drive On 24,21 Driving			

It seems like this bus had some technical problems as climate consumption was high again and compared to 4 from the OPENMATICS data it had no big differences.

Location 1 3-6 February 2019



Bus 2



166 Distance Travelled [km]	2,01 Average Consumption [kWh/km]	0,44 Recuperation [kWh/km]	0,54 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 6 180,00	Battery Consumption [kWh] 335 Total Consumption 90,43 Climate Consumption	Recuperation [kWh] 72,91 Total Recuperation	Temperature (C) 7,42 Average Outside Temperature 14 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 10,67 Main Switch On 15,91 E-Drive On 23,21 Driving			

Bus 4



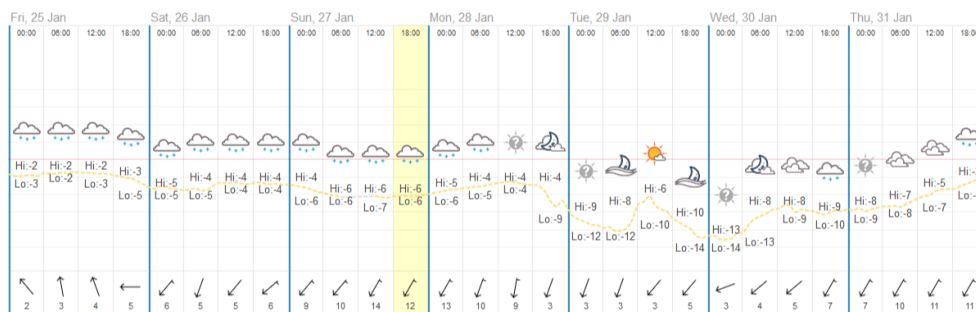
163 Distance Travelled [km]	1,98 Average Consumption [kWh/km]	0,43 Recuperation [kWh/km]	0,50 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 8 460,00	Battery Consumption [kWh] 322 Total Consumption	Recuperation [kWh] 70,62 Total Recuperation	Temperature (C) 7,42 Average Outside Temperature
Averages of Velocity [km/h] 6,29 Main Switch On 16,68 E-Drive On 24,53 Driving	81,43 Climate Consumption		14 Keskiarvo: HVAC_TEMP_InsideTe...

Bus 3



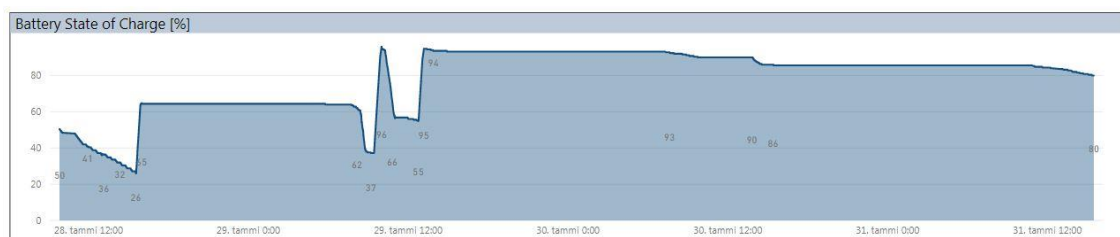
148 Distance Travelled [km]	2,35 Average Consumption [kWh/km]	0,42 Recuperation [kWh/km]	0,89 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 10 076,00	Battery Consumption [kWh] 348 Total Consumption	Recuperation [kWh] 61,87 Total Recuperation	Temperature (C) 7,42 Average Outside Temperature
Averages of Velocity [km/h] 11,20 Main Switch On 15,97 E-Drive On 21,74 Driving	131,59 Climate Consumption		14 Keskiarvo: HVAC_TEMP_InsideTe...

Location 2 25-31 January 2019



Temperatures at Location 2 were higher than average during the winter. This week was the coldest according to the data. The 29th and 30th of January were the two coldest days.

Bus 5

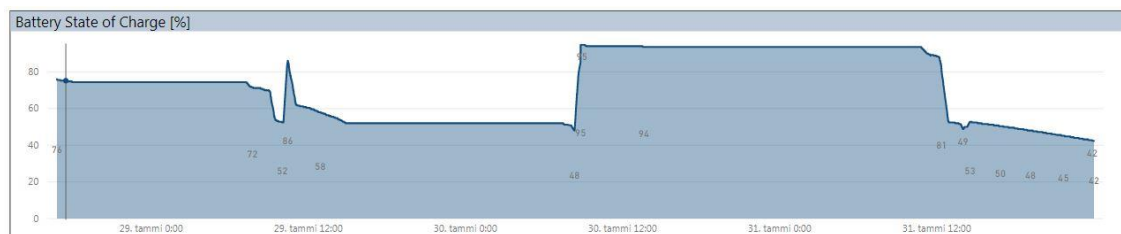


84 Distance Travelled [km]	1,37 Average Consumption [kWh/km]	0,17 Recuperation [kWh/km]	0,19 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 84,00	Battery Consumption [kWh] 115 Total Consumption 15,90 Climate Consumption	Recuperation [kWh] 14,71 Total Recuperation	Temperature (C) 5,19 Average Outside Temperature 12 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 4,68 Main Switch On 10,48 E-Drive On 38,52 Driving			

The SOC curve shows the bus had been driving only on the 29th of January. The bus had been driving partly highway speeds and not been stopping at bus stops. It is the first

example of how low the climate consumption per kilometer drops with higher speeds, since climate consumption is more time dependant rather than speed.

Bus 6



95 Distance Travelled [km]	1,71 Average Consumption [kWh/km]	0,29 Recuperation [kWh/km]	0,37 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 247,00	Battery Consumption [kWh] 163 Total Consumption 35,46 Climate Consumption	Recuperation [kWh] 27,71 Total Recuperation	Temperature (C) 5,19 Average Outside Temperature 12 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 3,38 Main Switch On 8,26 E-Drive On 40,90 Driving			

The bus had been standing long with only the main switch on, which might have biased the driveline consumption. The average speed was also higher than the other buses during this time.

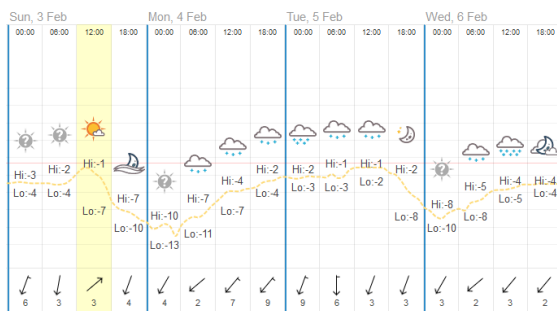
Bus 7



57 Distance Travelled [km]	1,29 Average Consumption [kWh/km]	0,29 Recuperation [kWh/km]	0,37 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 208,00	Battery Consumption [kWh] 74 Total Consumption 20,89 Climate Consumption	Recuperation [kWh] 16,85 Total Recuperation	Temperature (C) 5,19 Average Outside Temperature 12 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 6,41 Main Switch On 13,11 E-Drive On 25,32 Driving			

A few test drives were driven with this bus on the 30th of January. Driving and charging were most irregular of all the buses, but consumption data seems comparable to other buses with similar average speeds.

Location 2 3-6 February 2019



This was the second cold period in Location 2 during the winter. Four buses had been driving, though not very much.

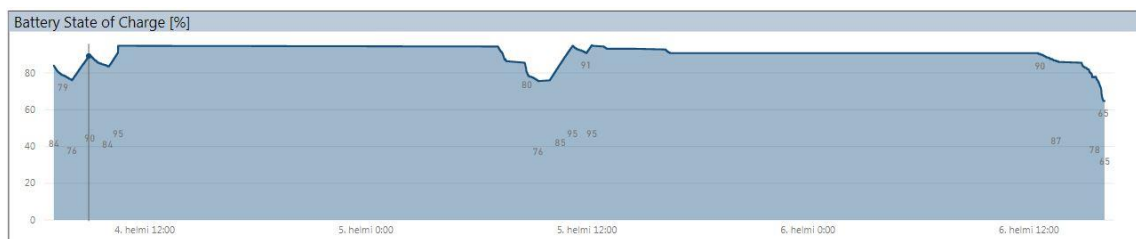
Bus 8



24 Distance Travelled [km]	1,17 Average Consumption [kWh/km]	0,35 Recuperation [kWh/km]	0,01 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 425,00	Battery Consumption [kWh] 29 Total Consumption 0,24 Climate Consumption	Recuperation [kWh] 8,45 Total Recuperation	Temperature (C) 7,42 Average Outside Temperature 14 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 3,87 Main Switch On 33,63 E-Drive On 37,85 Driving			

The data of this bus show only that with a small amount of driving and when the bus is already heated completely, the climate system does not need to heat the bus at all. This could be after preconditioning or starting from a warm garage.

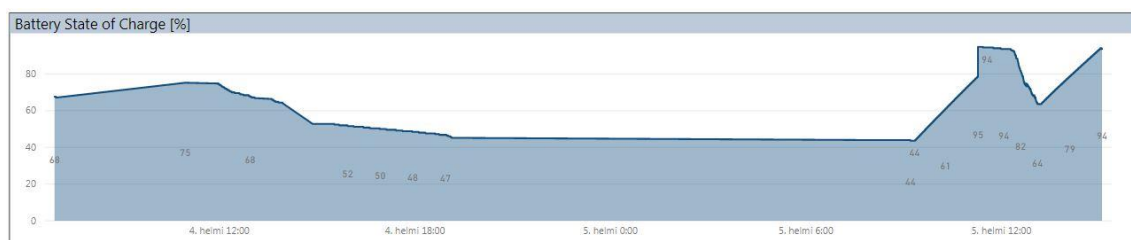
Bus 7



35 Distance Travelled [km]	1,48 Average Consumption [kWh/km]	0,27 Recuperation [kWh/km]	0,49 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 243,00	Battery Consumption [kWh] 51 Total Consumption 17,03 Climate Consumption	Recuperation [kWh] 9,45 Total Recuperation	Temperature (C) 7,42 Average Outside Temperature 14 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 3,41 Main Switch On 11,81 E-Drive On 23,33 Driving			

A few small trips were driven with this bus. The data shows very similar figures as seen before in a bus driving in a line.

Bus 9



38 Distance Travelled [km]	1,54 Average Consumption [kWh/km]	0,21 Recuperation [kWh/km]	0,46 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 146,00	Battery Consumption [kWh] 58 Total Consumption 17,45 Climate Consumption	Recuperation [kWh] 8,06 Total Recuperation	Temperature (C) 7,42 Average Outside Temperature 14 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 3,32 Main Switch On 5,85 E-Drive On 37,79 Driving			

The main switch on and E-Drive on average speeds show most of driving was carried out on the 5th of February which was the warmest day. On the 4th of February the bus had only been standing and draining slowly with very little driving. There was no data available from the 6th of February which means the bus was most likely powerless.

Bus 10



66 Distance Travelled [km]	1,19 Average Consumption [kWh/km]	0,25 Recuperation [kWh/km]	0,25 Climate Consumption [kWh/km]
Total Mileage of Vehicle [km] 72,00	Battery Consumption [kWh] 79 Total Consumption 16,34 Climate Consumption	Recuperation [kWh] 16,67 Total Recuperation	Temperature (C) 7,42 Average Outside Temperature 14 Keskiarvo: HVAC_TEMP_InsideTe...
Averages of Velocity [km/h] 3,24 Main Switch On 7,23 E-Drive On 38,03 Driving			

Most driving was done on the 5th of February on this bus as well. Driveline consumption was the lowest in this study.